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ARCHITECTURAL ACOUSTICS.*

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BECAUSE familiarity with the phenomena of sound has so far outstripped the adequate study of the problems involved, many of them have been popularly shrouded in a wholly unnecessary mystery. Of none, perhaps, is this more true than of architectural acoustics. The conditions surrounding the transmission of speech in an enclosed auditorium are complicated, it is true, but are only such as will yield an exact solution in the light of adequate data. It is, in other words, a rational engineering problem.

The problem of architectural acoustics is necessarily complex, and each room presents many conditions which contribute to the result in a greater or less degree, according to circumstances. To take justly into account these varied conditions, the solution of the problem should be quantitative, not merely qualitative; and to reach its highest usefulness and the dignity of an engineering science it should be such that its application can precede, not merely follow, the construction of the building.

In order that hearing may be good in any auditorium it is

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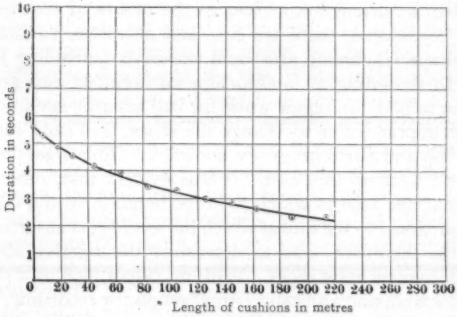
necessary that the sound should be sufficiently loud, that the simultaneous components of a complex sound should maintain their proper relative intensities, and that the successive sounds in rapidly-moving articulation, either of speech or of music, should be clear and distinct, free from each other and from extraneous noises. These three are the necessary, as they are the entirely sufficient, conditions for good hearing. Scientifically the problem involves three factors: reverberation, interference, and resonance. As an engineering problem it involves the shape of the auditorium, its dimensions, and the materials of which it is composed.

Sound, being energy, once produced in a confined space, will continue until it is either transmitted by the boundary walls or is transformed into some other kind of energy, generally heat. This process of decay is called absorption. Thus, in the lecture-room of Harvard University, in which, and in behalf of which, this investigation was begun, the rate of absorption was so small that a word spoken in an ordinary tone of voice was audible for five and a half seconds afterwards. During this time even a very deliberate speaker would have uttered the twelve or fifteen succeeding syllables. Thus the successive enunciations blended into a loud sound, through which and above which it was necessary to hear and distinguish the orderly progression of the speech. Across the room this could not be done; even near the speaker it could be done only with an effort wearisome in the extreme if long maintained. With an audience filling the room the conditions were not so bad, but still not tolerable. This may be regarded, if one so chooses, as a process of multiple reflection from walls, from ceiling, and from floor, first from one and then another, losing a little at each reflection until ultimately inaudible. This phenomenon will be called reverberation, including, as a special case, the echo. It must be observed, however, that, in general, reverberation results in a mass of sound filling the whole room and incapable of analysis into its distinct reflections. It is thus more difficult to recognize and impossible to locate. The term "echo" will be reserved for that particular case in which a short, sharp sound is distinctly repeated by reflection, either once from a single surface, or several times from two or more surfaces. In the general case of reverberation we are concerned only with the rate of decay of the sound. In the special case of the echo

we are concerned not merely with its intensity, but with the interval of time elapsing between the initial sound and the moment it reaches the observer. In the room mentioned as the occasion of this investigation no discrete echo was distinctly perceptible, and the case will serve excellently as an illustration of the more general type of reverberation. After preliminary gropings, first in the literature and then with several optical devices for measuring the intensity of sound, all established methods were abandoned. Instead, the rate of decay was measured by measuring what was inversely proportional to it—the duration of audibility of the reverberation, or, as it will be called here, the duration of audibility of the residual sound. These experiments may be explained to advantage here, for they will give more clearly than would abstract discussion an idea of the nature of reverberation. Broadly considered, there are two, and only two, variables in a room—shape (including size) and materials (including furnishings). In designing an auditorium an architect can give consideration to both; in repair work for bad acoustic conditions it is generally impracticable to change the shape, and only variations in materials and furnishings are allowable. This was, therefore, the line of work in this case. It was evident that, other things being equal, the rate at which the reverberation would disappear was proportional to the rate at which the sound was absorbed. The first work, therefore, was to determine the relative absorbing power of various substances. With an organ pipe as a constant source of sound, and a suitable chronograph for recording, the duration of audibility of a sound after the source had ceased in this room when empty was found to be 5.62 seconds. All the cushions from the seats in Sanders Theatre were then brought over and stored in the lobby. On bringing into the lecture-room a number of cushions, having a total length of 8.2 metres, the duration of audibility fell to 5.33 seconds. On bringing in 17 metres the sound in the room after the organ pipe ceased was audible for but 4.94 seconds. Evidently the cushions were strong absorbents and rapidly improving the room, at least to the extent of diminishing the reverberation. The result was interesting and the process was continued. Little by little the cushions were brought into the room, and each time the duration of audibility was measured. When all the seats (436 in number) were covered, the sound was audible for 2.03 seconds. Then the aisles were covered, and then

the platform. Still there were more cushions—almost half as many more. These were brought into the room, a few at a time, as before, and draped on a scaffolding that had been erected around the room, the duration of the sound being recorded each time. Finally, when all the cushions from a theatre seating nearly fifteen hundred persons were placed in the room—covering the seats, the aisles, the platform, the rear wall to the ceiling—the duration of audibility of the residual sound was 1.14 seconds. This experiment, requiring, of course, several nights' work, having been completed, all the cushions were removed and the room was in readiness for the test of other absorbents. It was evident

FIG. 1.



Curve showing the relation of the duration of the residual sound to the added absorbing material.

that a standard of comparison had been established. Curtains of chenille, 1.1 metres wide and 17 metres in total length, were draped in the room. The duration of audibility was then 4.51 seconds. Turning to the data that had just been collected, it appeared that this amount of chenille was equivalent to 30 metres of Sanders Theatre cushions. Oriental rugs (Herez, Demirjik, and Hindoostanee) were tested in a similar manner, as were also cretonne cloth, canvas, and hair-felt. Similar experiments, but in a smaller room, determined the absorbing power of a man and of a woman, always by determining the number of running metres of Sanders Theatre cushions that would produce the same effect. This process of comparing two absorbents by actually substituting

one for the other is laborious, and it is given here only to show the first steps in the development of a method. Without going into details, it is sufficient here to say that this method was so perfected as to give not merely relative, but absolute, coefficients of absorption.

In this manner a number of coefficients of absorption were determined for objects and materials which could be brought into and removed from the room, for sounds having a pitch an octave above middle C. In the following table the numerical values are the absolute coefficients of the absorption:

Oil paintings, inclusive of frames	.28
Carpet rugs	.20
Oriental rugs, extra heavy	.29
Cheese-cloth	.019
Cretonne cloth	.15
Shelia curtains	.23
Hair-felt, 2.5 Cm. thick, 8 Cm. from wall	.78
Cork, 2.5 Cm. thick, loose on floor	.16
Linoleum, loose on floor	.12

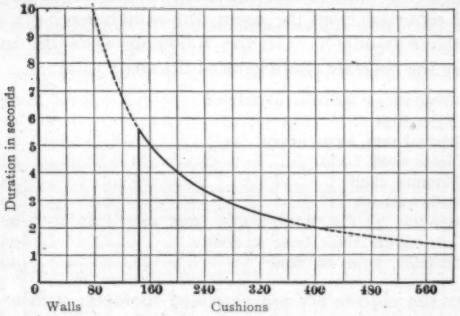
When the objects are not extended surfaces, such as carpets or rugs, but essentially spacial units, it is not easy to express the absorption as an absolute coefficient. In the following table the absorption of each object is expressed in terms of a square metre of complete absorption:

Audience, per person	.44
Isolated woman	.54
Isolated man	.48
Plain ash settees	.039
Plain ash settees, per single seat	.0077
Plain ash chairs, "bent wood"	.0082
Upholstered settees, hair and leather	1.10
Upholstered settees, per single seat	.28
Upholstered chairs similar in style	.30
Hair cushions, per seat	.21
Elastic-felt cushions, per seat	.20

Of even greater importance was the determination of the coefficient of absorption of floors, ceilings, and wall surfaces. The accomplishment of this called for a very considerable extension of the method adopted. If the reverberation in a room as changed by the addition of absorbing material be plotted, the resulting curve will be found to be a portion of an hyperbola with dis-

placed axes. An example of such a curve, as obtained in the lecture-room of the Fogg Art Museum, in Cambridge, is plotted in the adjacent diagram, Fig. 1. If now the origin of this curve be displaced so that the axes of coördinates are the asymptotes of the rectangular hyperbola, the displacement of the origin measures

FIG. 2.



Curve 5 plotted as part of its corresponding rectangular hyperbola. The solid part was determined experimentally; the displacement of this to the right measures the absorbing power of the walls of the room.

the initial absorbing power of the room, its floors, walls, and ceilings. Such experiments were carried out in a large number of rooms in which the different component materials entered in very different degrees, and an elimination between these different experiments gave the following coefficient of absorption for different materials:

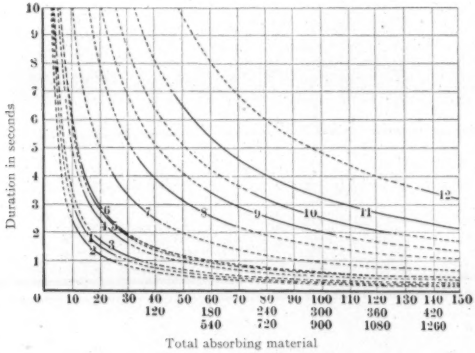
Open window	1.000
Wood-sheathing (hard pine)	.061
Plaster on wood-lath	.034
Plaster on wire-lath	.033
Glass, single thickness	.027
Plaster on tile	.025
Brick set in Portland cement	.025

If the experiments in these rooms are plotted in a single diagram, the result is a family of hyperbolæ showing a very interesting relationship to the volumes of the rooms. Indeed, if from these hyperbolas the parameter, which equals the product

of the coördinates, be determined, it will be found to be linearly proportional to the volume of the room. These results are plotted in Fig. 4, showing how strict the proportionality is even over a very great range in volume. We have thus at hand a ready method of calculating the reverberation for any room, its volume and the materials of which it is composed being known.

The first five years of the investigation were devoted to violin C, the C an octave above middle C, having a vibration frequency of 512 vibrations per second. This pitch was chosen because, in the art of telephony, it was regarded at that time as the character-

FIG. 3.



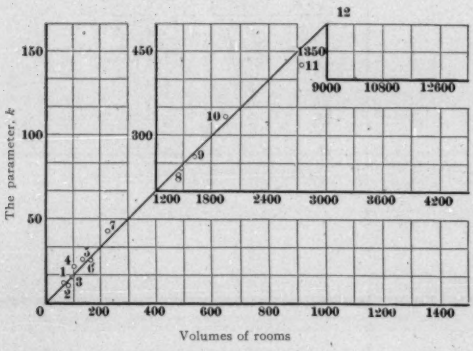
The curves of Figs. 8 and 9 entered as parts of their corresponding rectangular hyperbolas. Three scales are employed for the volumes, by groups 1–7, 8–11, and 12.

istic pitch determining the conditions of articulate speech. The planning of Symphony Hall in Boston forced an extension of this investigation to notes over the whole range of the musical scale, three octaves below and three octaves above violin C.

In the very nature of the problem, the most important datum is the absorption coefficient of an audience, and the determination of this was the first task undertaken. By means of a lecture on one of the recent developments of physics, wireless telegraphy, an audience was thus drawn together and at the end of the lecture requested to remain for the experiment. In this attempt the effort was made to determine the coefficients for the five octaves

from C_2128 to C_82048, including notes E and G in each octave. For several reasons the experiment was not a success. A threatening thunderstorm made the audience a small one, and the sultriness of the atmosphere made open windows necessary, while the attempt to cover so many notes, thirteen in all, prolonged the experiment beyond the endurance of the audience. While this experiment failed, another the following summer was more successful. In the year that had elapsed the necessity of carrying the investigation further than the limits intended became evident, and now the experiment was carried from C_164 to C_74096, but in-

FIG. 4.

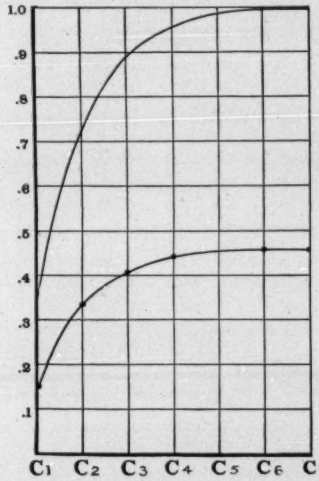


The parameters, k, plotted against the volumes of the rooms, showing the two proportional.

cluded only the C notes, seven notes in all. Moreover, bearing in mind the experiences of the previous summer, it was recognized that even seven notes would come dangerously near overtaxing the patience of the audience. Inasmuch as the coefficient of absorption for C_4512 had already been determined six years before, in the investigations mentioned, the coefficient for this note was not redetermined. The experiment was therefore carried out for the lower three and the upper three notes of the seven. The audience, on the night of this experiment, was much larger than that which came the previous summer, the night was a more comfortable one, and it was possible to close the windows during the experiment. The conditions were thus fairly satisfactory. In

order to get as much data as possible, and in as short a time, there were nine observers stationed at different points in the room. These observers, whose kindness and skill it is a pleasure to acknowledge, had prepared themselves, by previous practice, for this one experiment. The results of the experiment are shown on the lower curve in Fig. 5. This curve gives the coefficient of absorp-

FIG. 5.



The absorbing power of an audience for different notes. The lower curve represents the absorbing power of an audience per person. The upper curve represents the absorbing power of an audience per square metre as ordinarily seated. The vertical ordinates are expressed in terms of total absorption by a square metre of surface. For the upper curve the ordinates are thus the ordinary coefficients of absorption. The several notes are at octave intervals, as follows: C_{164}, C_{2128}, C_3 (middle C) 256, C_{4512}, C_{51024}, C_{62048}, C_{74096}.

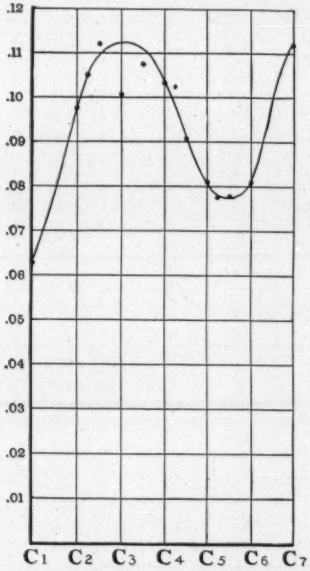
tion per person. It is to be observed that one of the points falls clearly off the smooth curve drawn through the other points. The observations on which this point is based were, however, much disturbed by a street car passing not far from the building, and the departure of this observation from the curve does not indicate a real departure in the coefficient, nor should it cast much doubt on the rest of the work, in view of the circumstances under which it was secured. Counteracting the, perhaps, bad impression which

this point may give, it is a considerable satisfaction to note how accurately the point for C_4512, determined six years before by a different set of observers, falls on the smooth curve through the remaining points. In the audience on which these observations were taken there were 77 women and 105 men. The courtesy of the audience in remaining for the experiment and the really remarkable silence which they maintained are gratefully acknowledged.

The next experiment was on the determination of the absorption of sound by wood sheathing. It is not an easy matter to find conditions suitable for this experiment. The room in which the absorption by wood sheathing was determined in the earlier experiments was not available for these. It was available then only because the building was new and empty. When these more elaborate experiments were under way the room became occupied, and in a manner that did not admit of its being cleared. Quite a little searching in the neighborhood of Boston failed to discover an entirely suitable room. The best one available adjoined a night lunch-room. The night lunch was bought out for a couple of nights, and the experiment was tried. The work of both nights was much disturbed. The traffic past the building did not stop until nearly two o'clock, and began again at four. The interest of those passing on foot throughout the night, and the necessity of repeated explanations to the police, greatly interfered with the work. This detailed statement of the conditions under which the experiment was tried is made by way of explanation of the irregularity of the observations recorded on the curve, and of the failure to carry this particular line of work further. The first night seven points were obtained for the seven notes C_164 to C_74096. The reduction of these results on the following day showed variations indicative of maxima and minima, which, to be accurately located, would require the determination of intermediate points. In the experiment the following night points were determined for the E and G notes in each octave between C_2128 and C_62048. Other points would have been determined, but time did not permit. It is obvious that the intermediate points in the lower and in the higher octave were desirable, but no pipes were to be had on such short notice for this part of the range, and in their absence the data could not be obtained. In the diagram, Fig. 6, the points lying on the vertical lines were determined

the first night. The points lying between the vertical lines were determined the second night. The accuracy with which these points fall on a smooth curve is, perhaps, all that could be expected in view of the difficulty under which the observations were conducted and the limited time available. One point in particular

FIG. 6.

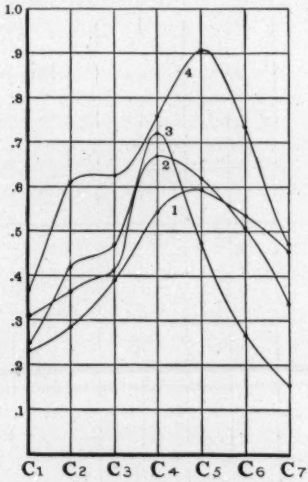


The absorbing power of wood sheathing, two centimetres thick, North Carolina pine. The observations were made under very unsuitable conditions. The absorption is here due almost wholly to yielding of the sheathing as a whole, the surface being shellacked, smooth, and non-porous. The curve shows one point of resonance within the range tested, and the probability of another point of resonance above. It is not possible now to learn as much in regard to the framing and arrangement of the studding in the particular room tested as is desirable. C_3 (middle C) 256.

falls far off from this curve, the point for C_3 256, by an amount which is, to say the least, serious, and which can be justified only by the conditions under which the work was done. The general trend of the curve seems, however, established beyond reasonable doubt. It is interesting to note that there is one point of maximum

absorption, which is due to resonance between the walls and the sound, and that this point of maximum absorption lies in the lower part, though not in the lowest part, of the range of pitch tested. It would have been interesting to determine, had the time and facilities permitted, the shape of the curve beyond C_7 4096, and to see if it rises indefinitely, or shows, as is far more likely, a succession of maxima.

FIG. 7.



The absorbing power of cushions. Curve 1 is for "Sanders Theatre" cushions of wiry vegetable fibre, covered with canvas ticking and a thin cloth. Curve 2 is for "Brooks House" cushions of long hair, covered with the same kind of ticking and plush. Curve 3 is for "Appleton Chapel" cushions of hair, covered with ticking and a thin leatherette. Curve 4 is for the elastic felt cushions of commerce, of elastic cotton, covered with ticking and short nap plush. The absorbing power is per square metre of surface. C_2 (middle C) 256.

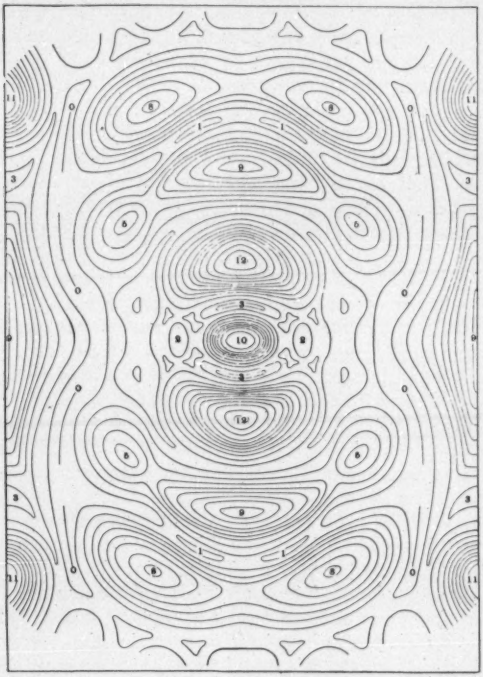
The experiment was then directed to the determination of the absorption of sound by cushions, and for this purpose return was made to the constant temperature room. Working in the manner indicated in the earlier papers for substances which could be carried in and out of a room, the curves represented in Fig. 7 were obtained. Curve 1 shows the absorption coefficient for the Sanders Theatre cushions, with which the whole investigation

was begun ten years ago. These cushions were of a particularly open grade of packing, a sort of wiry grass or vegetable fibre. They were covered with canvas ticking, and that, in turn, with a very thin cloth covering. Curve 2 is for cushions borrowed from the Phillips Brooks House. They were of a high grade, filled with long, curly hair, and covered with canvas ticking, which was, in turn, covered by a long nap plush. Curve 3 is for the cushion of Appleton Chapel, hair covered with a leatherette, and showing a sharper maximum and a more rapid diminution in absorption for the higher frequencies, as would be expected under such conditions. Curve 4 is probably the most interesting, because for more standard commercial conditions ordinarily used in churches. It is to be observed that all four curves fall off for the higher frequencies, all show a maximum located within an octave, and three of the curves show a curious hump in the second octave. This break in the curve is a genuine phenomenon, as it was tested time after time. It is perhaps due to a secondary resonance, and it is to be observed that it is the more pronounced in those curves that have the sharper resonance in their principal maxima.

In both articulate speech and in music the source of sound is rapidly and, in general, abruptly changing in pitch, quality, and loudness. In music one pitch is held during the length of a note. In articulate speech the unit or element of constancy is the syllable. Indeed, in speech it is even less than the length of a syllable, for the open vowel sound which forms the body of a syllable usually has a consonantal opening and closing. During the constancy of an element, either of music or of speech, a train of sound waves spreads spherically from the source, just as a train of circular waves spreads outward from a rocking boat on the surface of still water. Different portions of this train of spherical waves strike different surfaces of the auditorium and are reflected. After such reflection they begin to cross each other's paths. If their paths are so different in length that one train of waves has entirely passed before the other arrives at a particular point, the only phenomenon at that point is prolongation of the sound. If the space between the two trains of waves be sufficiently great, the effect will be that of an echo. If there be a number of such trains of waves thus widely spaced, the effect will be that of multiple echoes. On the other hand, if two trains of waves have travelled so nearly equal paths that they overlap, they will, de-

pendent on the difference in length of the paths which they had travelled, either reinforce or mutually destroy each other. Just as two equal trains of water waves crossing each other may entirely neutralize each other if the crest of one and the trough of the

FIG. 8.



Distribution of intensity on the head level in a room with a barrel-shaped ceiling, with centre of curvature on the floor level.

other arrive together, so two sounds, coming from the same source, in crossing each other may produce silence. This phenomenon is called interference, and is a common phenomenon in all types of wave motion. Of course, this phenomenon has its

complement. If the two trains of water waves so cross that the crest of one coincides with the crest of the other and trough with trough, the effects will be added together. If the two sound waves be similarly retarded, the one on the other, their effects will also be added. If the two trains of waves be equal in intensity, the combined intensity will be quadruple that of either of the trains separately, as above explained, or zero, depending on their relative retardation. The effect of this phenomenon is to produce regions in an auditorium of loudness and regions of comparative or even complete silence. It is a partial explanation of the so-called deaf regions in an auditorium.

It is not difficult to observe this phenomenon directly. It is difficult, however, to measure and record the phenomenon in such a manner as to permit of an accurate chart of the result. Without going into the details of the method employed, the result of these measurements for a room very similar to the Congregational Church in Naugatuck, Connecticut, is shown in the accompanying chart. The room experimented in was a simple, rectangular room with plain side walls and ends and with a barrel or cylindrical ceiling. The result is clearly represented in Fig. 8, in which the intensity of the sound has been indicated by contour lines in the manner employed in the drawing of the geodetic survey maps. The phenomenon indicated in these diagrams was not ephemeral, but was constant so long as the source of sound continued, and repeated itself with almost perfect accuracy day after day. Nor was the phenomenon one which could be observed merely instrumentally. To an observer moving about in the room it was quite as striking a phenomenon as the diagrams suggest. At the points in the room indicated as high maxima of intensity in the diagram the sound was so loud as to be disagreeable, at other points so low as to be scarcely audible. It should be added that this distribution of intensity is with the source of sound at the centre of the room. Had the source of sound been at one end and on the axis of the cylindrical ceiling, the distribution of intensity would still have been bilaterally symmetrical, but not symmetrical about the transverse axis.

When a source of sound is maintained constant for a sufficiently long time, a few seconds will ordinarily suffice: the sound becomes steady at every point in the room. The distribution of the intensity of sound under these conditions is called the inter-

FIG. 9.

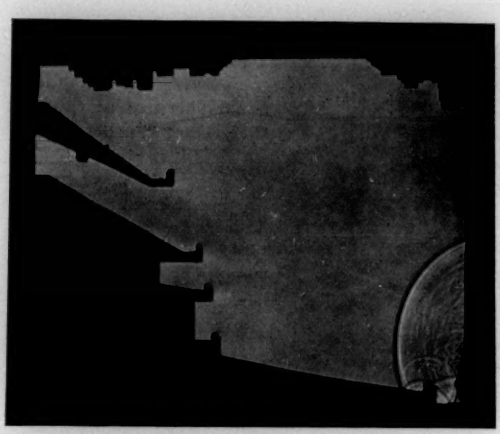


FIG. 10.

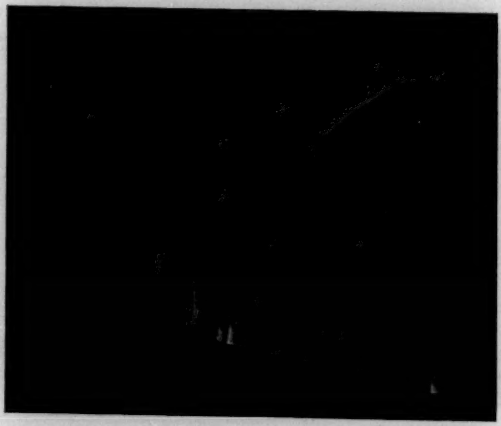


FIG. 11.

FIG. 12.

FIG. 13.

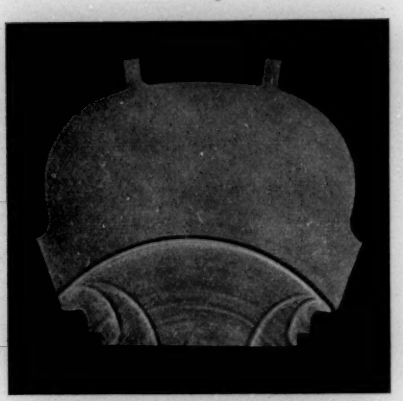
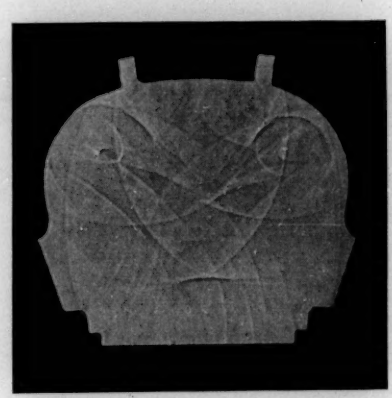


FIG. 14.

ference system, for that particular note, of the room or space in question. If the source of sound is suddenly stopped, it requires some time for the sound in the room to be absorbed. This pro-

FIG. 15.

FIG. 16.



longation of sound after the source has ceased is called reverberation. If the source of sound, instead of being maintained, is short and sharp, it travels as a discrete wave or group of waves about

the room, reflected from wall to wall, producing echoes. In the Greek theatre there was ordinarily but one echo, "doubling the case ending," while in the modern auditorium there are many, generally arriving at a less interval of time after the direct sound and therefore less distinguishable, but stronger and therefore more disturbing.

The formation and the propagation of echoes may be admirably studied by an adaptation of the so-called *schlieren-Methode* device for photographing air disturbances. It is sufficient here to say that the adaptation of this method to the problem in hand consists in the construction of a model of the auditorium to be studied to proper scale, and investigating the propagation through it of a proportionally scaled sound wave. To examine the formation of echoes in a vertical section, the sides of a model are taken off and, as the sound is passing through it, it is illuminated instantaneously by the light from a very fine and somewhat distant electric spark. In the accompanying illustrations, reduced from the photographs, the enframing silhouettes are shadows cast by the model, and all within are direct photographs of the actual sound wave and its echoes. The four photographs show the sound and its echoes at different stages in their propagation through the room, the particular auditorium under investigation being the New Theatre in New York. It is not difficult to identify the master wave and the various echoes which it generates, nor, knowing the velocity of sound, to compute the interval at which the echo is heard.

To show the generation of echoes and their propagation in a horizontal plane, the ceiling and floor of the model are removed and the photograph taken in a vertical direction. The photographs shown in Figs. 13 to 16 show the echoes produced in the horizontal plane passing through the marble parapet in front of the box.

While these several factors, reverberation, interference, and echo, in an auditorium at all complicated are themselves complicated, nevertheless they are capable of an exact solution, or, at least, of a solution as accurate as are the architect's plans in actual construction. And it is entirely possible to calculate in advance of construction whether or not an auditorium will be good, and, if not, to determine the factors contributing to its poor acoustics and a method for their correction.

AIR-GAP FLUX DISTRIBUTION IN DYNAMO-ELECTRIC GENERATORS.*

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An experienced designer may go far and obtain good results without resorting to the more or less tedious process of plotting flux distribution curves; but occasions arise when his experience and judgment fail him, and when a reasonably accurate method of predetermining the distribution of flux density over the surface of the armature would give him all necessary information. A method of designing electric machinery—whether continuous-current dynamos or alternating-current generators—which involves the plotting of the flux distribution curves, has much to recommend it, not only to the student, but also to the professional designer. The advantage from the student's and teacher's point of view is that a more real and accurate conception of the operating conditions can be obtained than by using empirical formulas, or making the unscientific assumptions which are otherwise necessary. The designer will be glad to avail himself of a practical method of plotting flux curves when departures have to be made from standard models, or when it is desired to investigate thoroughly the effects of cross-magnetization upon commutation or pressure regulation.

The procedure about to be described is based upon the early work of Professor W. E. Goldsborough,[1] and is a modification of the method outlined by Professor Charles R. Moore in his paper on "Air-Gap Flux Distribution in Direct-Current Machines."[2] It is followed by the students of the School of Electrical Engineering, Purdue University, in the courses of Electrical Design, and it has been found to give results agreeing very

* Communicated by the Author.

[1] *Transactions A. I. E. E.*, vol. 15, p. 515; vol. 16, p. 461, and vol. 17, p. 679.

[2] *Transactions A. I. E. E.*, vol. 31, p. 509.

closely with experimental measurements made on a number of commercial machines. The method—which is capable of still further elaboration—will be explained as briefly as possible; but the ground cannot be covered adequately without dwelling on a few points that have been discussed in some detail by the writers previously referred to. The present writer's chief claim to originality lies in the method of deriving the curves giving the distribution of M.M.F. over the armature surface, which he believes to be new. It is usual to make more or less reasonable guesses as to the probable resultant M.M.F. at the various points on the armature surface when the demagnetizing influence of adjacent poles is taken into account, and this sometimes leads to unreliable conclusions.

The method proposed by Professor Goldsborough for predetermining the distribution of flux density over the armature surface assumes a smooth-core armature. It is true that he also considers the case of slotted armatures, but the application of his method to any but smooth cores involves so many measurements and detailed computations as to render it unpractical. If a method is to be of real practical utility it must include the common case of the slotted armature, and the writer believes that the Goldsborough method in its simplest form may conveniently be used if the slotted armature is replaced by an imaginary smooth-core armature of the proper "equivalent" diameter. It will, therefore, be well to consider, in the first place, what is to be understood by the equivalent air-gap.

AIR-GAP FLUX DISTRIBUTION WITH TOOTHED ARMATURES.

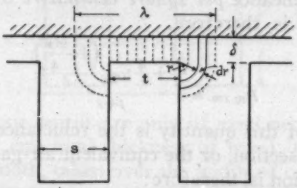
The determination of the flux densities in all parts of the tooth and slot for various values of the average air-gap flux density is so difficult and complicated a problem that it is safe to say no correct mathematical solution may be looked for, although empirical rules and formulas of great practical value may serve the purpose of the designer.

The reluctance of the magnetic paths between pole face and armature core can be calculated with but little error for the two extreme cases of very low and very high average flux density over the tooth pitch; but for intermediate values the designer

has still to rely on his judgment, based on familiarity with the laws of the magnetic circuit.

To calculate the permeance of the air paths over one slot pitch at the centre of the pole face, when the density is low, the magnetic lines are supposed to follow the paths indicated in Fig. 1. The tooth is drawn, for convenience, with parallel sides, and the magnetic lines entering the sides of the tooth are supposed to follow a path consisting of a straight portion of length δ, equal to the actual clearance, and a circular arc of radius r, all as indicated in the figure. This is obviously an arbitrary assumption, but it is convenient for calculation and gives very good results. It agrees very closely with the results obtained by Messrs. H. S. Hele-Shaw, Alfred Hay, and P. H. Powell in their classic

FIG. 1.



Institution paper,[3] and also with the *correct* mathematical conclusions arrived at by Mr. F. W. Carter,[4] based on certain assumptions, including that of infinite permeability of the iron in the teeth.

Considering a portion of the air-gap one centimetre long axially (*i.e.*, in a direction normal to the plane of the section shown in Fig. 1.), the permeance over the slot pitch of width λ is seen to be made up of two parts: (1) the permeance P_1 between pole face and top of tooth, of value $P_1 = \frac{t}{\delta}$, and (2) the permeance $2P_2$ where P_2 is the permeance between the pole face and one side of the tooth. Consider any small section of thickness

[3] "Hydrodynamical and Electromagnetic Investigations Regarding the Magnetic-flux Distribution in Toothed-core Armatures," *Proc. Inst. E. E.*, vol. 34, p. 21.

[4] *Electrical World*, vol. 38, Nov. 30, 1901, p. 884.

dr as indicated in Fig. 1. The permeance of such a path, of depth one centimetre measured axially, is

$$dP_2 = \frac{dr}{\delta + \frac{\pi}{2}r}$$

$$= \frac{2}{\pi} \times \frac{dr}{\left(\frac{2\delta}{\pi}\right) + r}$$

and

$$P_2 = \frac{2}{\pi} \int_0^{\frac{s}{2}} \frac{dr}{\frac{2\delta}{\pi} + r}$$

$$= \frac{2}{\pi} \log_e \frac{\delta + \frac{\pi s}{4}}{\delta}$$

The average permeance *per square centimetre* over the slot pitch at centre of pole is, therefore,

$$P_{sq.\,cm.} = \frac{\frac{t}{\delta} + \frac{4}{\pi} \log_e \frac{\left(\delta + \frac{\pi s}{4}\right)}{\delta}}{t+s} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

The reciprocal of this quantity is the reluctance per square centimetre of cross-section, or the equivalent air-gap length δ_e. The required expression is, therefore:

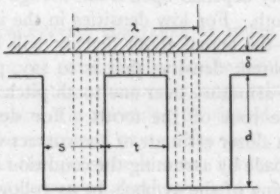
$$\delta_e = \frac{t+s}{\frac{t}{\delta} + \frac{4}{\pi} \log_e \left(\frac{\pi s}{4\delta} + 1\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)^5$$

Consider now Fig. 2, which illustrates the case of a highly saturated tooth. The lines of flux are shown parallel over the whole of the slot pitch, a condition which is approached—but never attained—as the density in the tooth is forced up to higher and higher values. It is obviously only when the permeability of the iron in the tooth becomes equal to unity—that is to say, equal to the permeability of the air paths—that this parallelism of the flux lines would occur, and the equivalent air-gap would be $\delta_e = \delta$, to which would have to be added another air-gap of

[5] If the ventilating ducts are closely spaced, or exceptionally wide, the gap, δ_e, for the equivalent smooth-core armature, as given by formula (2), might have to be slightly modified; but the calculation of fringing at the sides of vent ducts is usually an unnecessary refinement.

length d to represent the reluctance of the teeth and slots. This is an extreme, and indeed an impossible, condition; but, since the actual distribution of the lines of flux in tooth and slot cannot be predetermined, the calculations for very high densities are usually made by assuming the flux lines to be parallel, as indicated in Fig. 2. It is when this assumption is made for low values of the density that errors are likely to be introduced. The following method of calculating the joint reluctance of tooth and slot should not be used for tooth densities below 20,000 gausses

FIG. 2.



Considering one centimetre only of axial net length of armature core (*i.e.*, 1 cm. total thickness of iron), the reluctance of the air-gap and tooth, taken over the width of one tooth only, is,

$$R_1 = \frac{\delta}{t} + \frac{d}{\mu t} = \frac{(d+\mu\delta)}{\mu t}$$

The reluctance of the slot portion of the total tooth pitch is,

$$R_2 = \frac{(d+\delta)}{s}$$

The air-gap of the equivalent smooth-core armature—being the reluctance per square centimetre—is, therefore,

$$\delta_e = \frac{(t+s)}{\frac{1}{R_1} + \frac{1}{R_2}}$$

which can be put in the form,

$$\delta_e = \frac{(t+s)(d+\delta)}{\mu t\left(\frac{d+\delta}{d+\mu\delta}\right)+s} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

This equivalent air-gap includes the reluctance of the tooth itself when the flux density is high. It is seen to depend upon the permeability of the iron, and, therefore, upon the actual flux

density in the tooth. In order to make use of formula (3), a value for the flux density in the tooth must be assumed. A method of working which involves a change in the equivalent air-gap for various values of the flux density would be unpractical, and, since no exact method is ever likely to be developed, some sort of compromise must be made. It is convenient to think of the reluctance of air-gap, teeth, and slots as consisting of two reluctances in series, (*a*) the reluctance of the equivalent air-gap (as calculated by formula (2) for the centre of the pole face), and (*b*) the reluctance of the tooth. The calculation of this latter quantity depends upon a knowledge of the actual flux density in the tooth. For low densities in the iron—up to about 20,000 gausses—the actual tooth density will be approximately equal to the apparent density; that is to say, practically all the flux entering the armature over one tooth pitch will pass into the core through the root of the tooth. For densities exceeding 20,000 gausses, a closer estimate of the correct value of the tooth density may be made by assuming the condition of Fig. 2.

Let the meaning of the symbols be as follows:

B_g = the average air-gap density at armature surface; *i.e.*, the average density over one tooth pitch of width $\lambda = t + s$.
B_t = the actual tooth density.
B_s = the density in the slot.

Then, on the asumption that the lines of flux are truly parallel, the total flux over net axial length of one centimetre may be written,

$$\phi_\lambda = (t+s)B_g \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

or

$$\phi_\lambda = tB_t + sB_s \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

It is possible to express B_g in terms of B_t and other known quantities, because the M.M.F. required to overcome the reluctance of air-gap proper and tooth is the same as that required to overcome the reluctance of air-gap proper and slot, seeing that these paths are in parallel between what may be considered equipotential surfaces; thus,

$$B_s(d+\delta) = B_t\left(\frac{d}{\mu} + \delta\right)$$

and

$$B_s = B_t \frac{d+\mu\delta}{\mu(d+\delta)}$$

By substituting this value of B_s in formula (5), and equating (4) and (5), the relation between tooth density and average air-gap density is obtained. This relation is,

$$B_g = B_t \frac{t + \frac{(d+\mu\delta)s}{\mu(d+\delta)}}{(t+s)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (6)$$

By assuming values of B_t ranging between 20,000 and (say) 26,000 gausses, the corresponding values of B_g can be calculated by formula (6), and a curve plotted from which values of B_t can be found when B_g is known.

CORRECTION FOR TAPER OF TOOTH.

The assumption of parallel sides to the tooth is justified only when the diameter of the armature is large relatively to the slot pitch. The dimension t in formula (6) should, in the first place, be the width of the narrowest part of the tooth, as it is important that the density at this point be known; it rarely exceeds 24,000 gausses in continuous-current machines, and is less in alternators. When the field system revolves, as in most modern alternators, the armature teeth will usually be wider at the root than at the top, and but little error will be introduced by taking for t the average width, for the purpose of calculating the average density B_t and the ampère-turns required for the teeth. It may further be mentioned that, since the tooth density rarely exceeds 20,000 lines per square centimetre in alternating-current machines, the formula (6) is not applicable. The assumption then made is that the whole of the flux over one slot pitch passes through the iron of the tooth; which leads to the relation

$$B_t = B_g \frac{(t+s)}{t} \frac{L_g}{L_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

where L_g and L_n stand respectively for the gross and net lengths of the armature core.

The case of a tooth with considerable taper, in which the density at root is in excess of 10,000 gausses, may be dealt with by the application of Simpson's rule. Having determined the density B_t at the root of the tooth, by applying formula (6) or (7) as the case may demand, the assumption is then made that

the total flux in the tooth remains unaltered through other parallel sections.[6]

The value of the magnetizing force H (or the ampère-turns required per unit length) can then be determined for any section of the tooth by referring to the B–H curves for the iron used in the armature. It is sufficient to determine H for three sections only.

Let these values be:

H_n at narrowest section

H_w at widest section

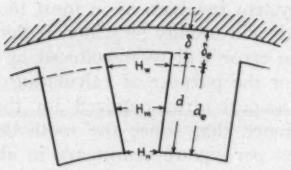
H_m at centre (*i.e.*, where the value of B_m is $\frac{B_n+B_w}{2}$)

Then, if the portion of B–H curve involved is supposed to be a parabola, Simpson's approximation is,

$$\text{Average } H=\tfrac{1}{6}H_n+\tfrac{4}{6}H_m+\tfrac{1}{6}H_w \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Referring to Fig. 3, it will be seen that H_w is taken at the section which would be the top of the tooth if the air-gap were

FIG. 3.



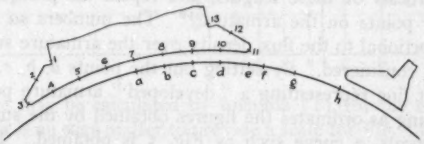
increased from δ to the "equivalent" value δ_e as calculated by formula (2). This is recommended as a good practical compromise; and the M.M.F. in gilberts required to overcome the reluctance of the tooth is $H \times d_e$ where d_e, the equivalent length of tooth, must be expressed in centimetres. If preferred, the formula (8) can be modified to give an average value of the necessary ampère-turns per inch.

[6] This is not a correct assumption when the root density is very high, because in that case flux will leak out from the sides of the tooth to the bottom of the slot; and at some distance from the bottom of slot (the taper being as indicated in Fig. 3) the total flux in the tooth will be greater than at the root cross-section.

VARIATION OF PERMEANCE OVER POLE PITCH.

The permeance per square centimetre of the air-gap when the armature is slotted may be calculated *for the centre of the pole face*, by using formula (1). This value will not change appreciably for other points under the pole shoe if the bore of the field magnets is concentric with the armature; but near the pole tips, and in the interpolar space, it will decrease at a more or less rapid rate, depending on the geometric configuration of the pole pieces, and their circumferential width relatively to pole pitch and air-gap length. Professor Goldsborough, in the series of papers previously referred to, considers a narrow section normal to the shaft through pole and armature; he then makes certain assumptions which cannot reasonably be disputed, and derives a curve showing the distribution of flux density over the surface of the armature. The method about to be explained is

FIG. 4.



based on this work of Professor Goldsborough, as modified and elaborated by Professor C. R. Moore. Let the pole shoe in Fig. 4 be thought of as unaffected by the neighboring poles. It tends to send flux into the armature; and if the very reasonable assumption is made that the pole shoe is an equipotential surface, the density of the flux entering the armature will, at every point on the armature periphery, be proportional to the permeance between that point and the surface of the pole shoe as shown in the figure. The assumption is that, whatever may be the M.M.F. tending to send flux from the point *a* on armature to the point 7 on pole (see Fig. 4), the same M.M.F. tends to send flux between any other two points, such as $a - 10$ or $d - 2$.

Set out a number of *equally spaced* points on the pole shoe, and consider each one as the centre of a small surface from which flux tends to go to any given point on the armature, such as *d*, considered also as the centre of a small surface. The drop of po-

tential along a line such as $d-7$ is assumed the same as that along any other line, such as $d-12$,[7] and the magnetic force at d due to the small surface 7 is $\frac{\text{M.M.F.}}{\text{length } (d-7)}$, while the magnetic force due to the small surface 12 is $\frac{\text{M. M.F.}}{\text{length } (d-12)}$; that is to say, it is proportional to the *reciprocal* of the distance between the points considered.[8]

The method of procedure may be summed up as follows:

Draw to any convenient scale a section through one pole shoe and the armature core, making the diameter of the latter such that the clearance at the centre is the equivalent air-gap δ_e as calculated by formula (2). Set off a number of equally spaced points on the pole shoe surface, and a number of points (not necessarily equally spaced) on the armature surface.[9] Measure the length of the shortest air path between any one point on the armature and *all* the points on the pole face. Take the sum of the reciprocals of these lengths, and repeat the process for all the other points on the armature.[10] The numbers so obtained are proportional to the flux density over the armature surface at the point considered. By setting out the points *a*, *b*, *c*, etc., on a straight line representing a "developed" armature periphery, and plotting as ordinates the figures obtained by the summation of reciprocals, a curve such as Fig. 5 is obtained. This is a graphic representation of the flux distribution over armature surface if the one pole is considered as acting alone, the other poles being so far removed that they have no influence on this distribution.

For a given value of the M.M.F. this curve could be plotted

[7] Measured as the shortest distance in air, *not* through the iron of the pole shoe.

[8] The law of squares does not apply here, because the section considered involves the idea of other parallel sections on each side, the effect of which is to keep all the flux lines within the section, *i.e.*, in the plane of the paper on which Fig. 4 is drawn.

[9] A distribution of armature points as indicated on Fig. 4 will give good results. The points *a*, *b*, *c*, *d*, and *e* should be chosen immediately below the corresponding points on the pole; otherwise, when the measurements are taken, the shortest distance from pole face to armature—which it is important to know—would not be included.

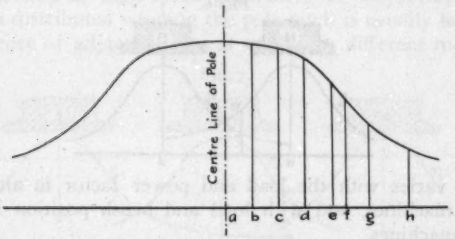
[10] On account of symmetry, it is not necessary to take armature points on both sides of the centre line.

in terms of the gausses, or lines per square centimetre, entering the armature at any point on the surface. But,

Flux per square centimetre $= B =$ *M.M.F.* $\times$ Permeance per sq. cm.,

from which it is seen that the curve can be calibrated to indicate the permeance per square centimetre of armature surface between any point on the armature surface and the pole shoe considered as an equipotential surface. The ordinates of the curve as drawn are of arbitrary height, depending upon the scale used in taking the measurements; but, since a value for permeance per square

FIG. 5.



centimetre may be calculated by formula (1) for the centre of the pole, it is an easy matter to provide a scale for Fig. 5 by which the air-gap permeance per square centimetre can be read for any point on the armature circumference.

EFFECT OF NEIGHBORING POLES.

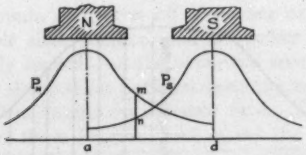
In Fig. 6 the N and S poles are shown close together, as they would be in an actual machine. They are supposed to be excited with the same number of ampère-turns. The permeance curve for the pole N is marked P_N, while an exactly similar curve for pole S is marked P_S. Each of these curves would also represent the flux distribution over armature surface if the corresponding pole were acting alone. As it is, the magnetic force, and therefore the flux density, at the point d will be the difference between a number of magnetic lines from the pole N, proportional to the ordinate dm, and a number of magnetic lines from the pole S, proportional to the ordinate dn; or, in general terms,

$$B = (M.M.F.) \times (P_N - P_S)$$

where (*M.M.F.*) is 0.4π times the ampère-turns on one pole.

The flux actually passing from the pole N into one square centimetre of the armature surface at the point d will no longer be dm, but $(dm - dn)$; and this suggests a convenient way of working which involves the idea of a *resultant M.M.F.* tending to send flux to any *one pole* from any point on the armature surface. The armature points considered must obviously lie within the limits of the pole pitch as measured between two neutral zones on the armature surface. By neutral zone is meant, not the geometric neutral, or point midway between two poles, but the zone where the flux neither enters nor leaves the armature: its

FIG. 6.



position varies with the load and power factor in alternating-current machines, and with load and brush position in direct-current machines.

Let $(M.M.F.)$ = the ampère-turns on any one pole,

$(M.M.F.)_d$ = the resultant M.M.F. due to field excitation, the point d,

B_d = the average flux density (gausses) in air-gap at point d of armature surface,

P_{Nd} = the permeance, armature to pole N, at point d,

P_{Sd} = the permeance, armature to pole S, at point d,

then

$$B_d = (M.M.F.)_d \times P_{Nd} = (M.M.F.) \times (P_{Nd} - P_{Sd})$$

and

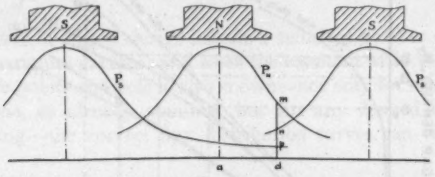
$$(M.M.F.)_d = (M.M.F.) \times \frac{P_{Nd} - P_{Sd}}{P_{Nd}} \quad \ldots\ldots\ldots (9)$$

In this manner a curve of resultant M.M.F. for open-circuit conditions can be drawn, provided the shape of pole shoe and length of air-gap have previously been decided upon, and the permeance curve plotted. It may be mentioned that, although two poles only have been shown in Fig. 6, the demagnetizing effect of the poles on both sides of the pole considered should be

taken into account. This leads to Fig. 7, from which it will be seen that the quantity P_{Sd} in formula (9) should actually be $(dn+dp)$. The influence of poles still farther removed is inappreciable, and need not be considered. It is, in fact, doubtful whether or not the correction for demagnetizing action of neighboring poles is of much value for points other than those in the interpolar space, because it is difficult to allow for the shading effect of the iron pole shoes. In other words, the height of the ordinate dp of Fig. 7 (which is in any case very small) cannot be accurately determined.

In the case of high-speed generators of the revolving field type with distributed winding the pole pitch is usually large, and the influence of adjacent poles is small. A different method of

FIG. 7.



procedure for obtaining the open-circuit M.M.F. curve is then to be preferred; but this will be explained later, in order that the development of the problem under consideration shall not be delayed.

OPEN-CIRCUIT FLUX DISTRIBUTION CURVES AS INFLUENCED BY TOOTH SATURATION.

Before considering the effect of the armature current in altering the distribution of magnetizing force over the armature periphery, it seems desirable to examine briefly how the degree of saturation of the teeth may be taken into account, and a correct flux distribution curve plotted. The method about to be explained is due to Professor C. R. Moore: it is probably more easily applied and less tedious than an equally scientific method more recently proposed by Dr. Alfred Hay.[11] If it is understood that the permeance curve as shown in Fig. 5 has been drawn and

[11] "Predetermining Field Distortion in Continuous-current Generators," A. Hay, *Electrician*, 72, pp. 283–285, Nov. 21, 1913.

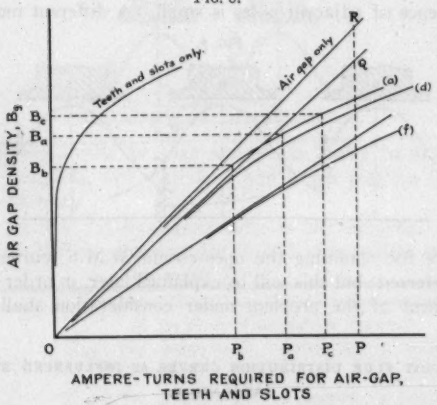
calibrated to read air-gap permeance per square centimetre of armature surface, it follows that, for a given value of M.M.F. between pole and armature, the flux density at any point—as for instance *d*—will be

$B_d = (\text{M.M.F.})_d \times$ value of ordinate of Fig. 5 at *d*,

but in order to get the flux into the armature core the reluctance of the teeth must be considered.

For any value of the air-gap density B_g there is a corresponding value of the tooth density, B_t, which can be calculated by formula (6) or (7), as the case demands; and the ampère-turns required to overcome the reluctance of the tooth can be found, all

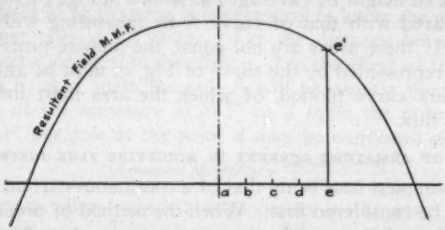
FIG. 8.



as previously explained. This value can be plotted in Fig. 8 against the corresponding values of B_g, and the resulting curve shows the excitation required to overcome tooth reluctance for all values of the air-gap density. The curves for the air-gap proper will all be straight lines when plotted in Fig. 8. Let OR be the curve for the point *a* at centre of pole. Add the ampère-turns required for the teeth, and obtain curve (a), which gives directly the ampère-turns required to overcome reluctance of air-gap, teeth, and slots, for all values of the air-gap density. It will be understood that the ordinates represent the average value of the air-gap density at armature surface over a slot pitch. Any

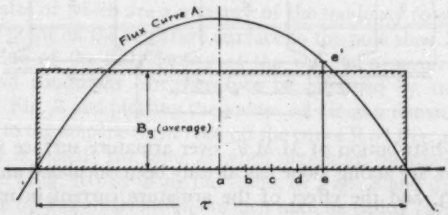
other curve, such as (d), is obtained by first drawing a straight line OQ such that PQ bears to PR the same relation as the ordinate at *a* in Fig. 5 bears to the ordinate at *d*, and then adding thereto the ampère-turns for the teeth, as already obtained.

FIG. 9.



The curves of Fig. 8 should include a sufficient number of points on the armature surface; and when the resultant M.M.F. between armature points and pole is also known—not only for open-circuit conditions, as already obtained, but for any desired condition of loading—the correct flux distribution curves can readily be plotted.

FIG. 10.



Let the curve of Fig. 9 represent the distribution of the resultant field M.M.F. on open circuit; then, at any point such as *e*, the M.M.F. is given by the length of the ordinate *ee'*. Find this value on the horizontal scale of Fig. 8, and the height of the ordinate at this point, where it meets curve *e* (which is not drawn in Fig. 8), is the flux density, which can be plotted as *ee'* in Fig. 10. In this manner the flux curve A of Fig. 10 is obtained. The area of this curve, taken between any given points on the armature periphery, is obviously a measure of the total flux entering the

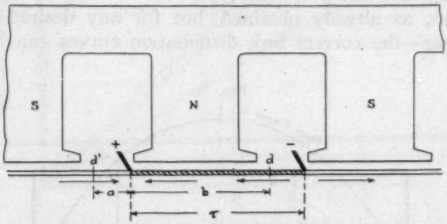
armature between those points. The required flux per pole is usually known. The average density over the pole pitch, τ, is, therefore, B_g (*average*) $= \frac{\phi}{\tau L_g}$

where L_g is the gross length of armature. By drawing the dotted rectangle of height B_g (average) as shown in Fig. 10, its area can be compared with that of curve A by measuring with a planimeter. If these areas are not equal, the ampère-turns per field pole, as represented by the curve of Fig. 9, must be altered, and a new flux curve plotted, of which the area must indicate the required flux.

EFFECT OF ARMATURE CURRENT IN MODIFYING FLUX DISTRIBUTION.

The simplest case being that of a continuous-current machine, this will be considered first. When the method of procedure has been explained, the modifications necessary to adapt it to alternating-current machinery will be discussed.

FIG. 11.



The distribution of M.M.F. over armature surface when the field poles are acting alone has already been calculated and plotted in Fig. 9, and the effect of the armature current in modifying this distribution may be ascertained by noting that the armature ampère-turns between any two points such as d and d' on the armature circumference (see Fig. 11) are $q\ (b-a)$ where q stands for the specific loading, or the ampère-conductors per unit length of armature circumference.

Let p = number of poles,

Z = total number of conductors on armature surface,

I_c = current in each conductor,

τ = pole pitch,

then $q = \frac{ZI_c}{p\tau}$

and the armature M.M.F. tending to modify the flux due to the field poles alone is,

$$0.4\pi\frac{ZI_c(b-a)}{p\quad\tau}$$

between the points d and d'.

In order that a curve may be plotted on the same basis as the resultant field M.M.F. curve, it is necessary to know the armature M.M.F. per pole at all points. Let the distance between the points d and d' be equal to the pitch τ, then the effect of the armature M.M.F. at d' upon the pole S will be exactly the same as the effect of the armature M.M.F. at d upon the pole N, and the M.M.F. *per pole* at the point d may be expressed as,

$$(Armature\ M.M.F.)_d = \frac{0.4\pi ZI_c(b-a)}{2p\quad\tau} \quad \ldots\ldots\ldots (10)$$

Its maximum value—which always occurs in the zone of commutation—is,

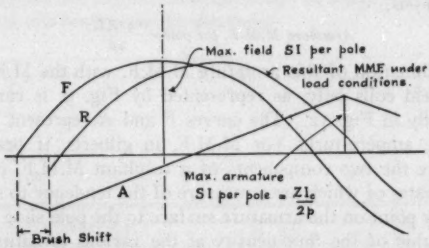
$$Armature\ M.M.F.\ per\ pole = \frac{0.4\pi ZI_c}{2p} \quad \ldots\ldots\ldots\ldots (11)$$

The combination of this armature M.M.F. with the M.M.F. due to the field coils only, as represented by Fig. 9, is carried out graphically in Fig. 12. The curves F and A represent field and armature ampère-turns (or M.M.F. in gilberts, if preferred). These are the two components of a resultant M.M.F. curve, R, the ordinates of which are a measure of the tendency to send flux from any point on the armature surface to the pole shoe N. The actual value of the flux density at the various armature points under load conditions can therefore be obtained by using the curves of Fig. 8 and plotting the values of air-gap density corresponding to the ampère-turns read off the curve R of Fig. 12. The procedure is exactly the same as when obtaining the open-circuit flux curve (Fig. 10) by using the values of Figs. 8 and 9; but the new curve of flux distribution—which may be called curve B, to distinguish it from the open-circuit flux curve A—gives the distribution over armature surface for a given brush position and a specified output. The difference in area of curves A and B is a measure of the flux lost through armature reaction: it includes not only direct demagnetization, but also cross magnetization which—by producing distortion of the flux distribution—leads sometimes to local concentration of high densities and reduction of total flux owing to saturation of the iron in the armature teeth.

The final flux curve for the loaded machine is generally similar

to curve B, except that its area must be such as to indicate that the desired voltage will be generated. This increased area is, of course, obtained by increasing the field ampère-turns. In other words, a new curve F is required in Fig. 12 such that the curve R resulting from its combination with the existing curve A will produce a new flux curve similar to B, but of the required area. This new flux distribution curve may be called curve C, to distinguish it from the open-circuit curve A and the flux curve B, which, although a load curve, has too small an average ordinate to generate the required voltage. The amount by which the ordinates of curve F should be increased may be found by trial, but it is generally possible to estimate the necessary correction to give the required result. The added field ampère-turns may be thought of as compensating for two distinct effects:

FIG. 12.



(1) The loss of pressure due to armature reaction,

(2) The loss of pressure due to IR drop in armature, brush contacts, and series field windings.[12]

The correction for (1) consists in bringing the total flux up to its value on open circuit. It is the ampère-turns necessary to raise the average air-gap density from its value over curve B to its value over curve A. An approximate method of making this correction is to find on curve (a) of Fig. 8 (*i.e.*, the curve corresponding to point *a* at centre of pole) the ampère-turns P_bP_a required to produce the difference of flux density B_bB_a when OB_b = average flux density over curve B, and OB_a = average flux density over curve A. The correction for (2) consists in increasing the flux per pole to such an extent that it will generate

[12] In alternating-current machines the reactance drop has also to be considered.

the increased voltage. This is the correction for compounding; it compensates for all internal loss of pressure, and must include over-compounding if this is called for.

If E' = required full load *developed* volts, and
E = open circuit terminal volts (being also the no-load developed volts), then,

$$\frac{\text{Area of curve C}}{\text{Area of curve A}} = \frac{E'}{E}$$

In this manner the required area of curve C is obtained. The average flux density must be increased in this proportion, and the necessary additional ampère-turns for this correction are arrived at approximately by making $P_a P_c$ (as indicated on Fig. 8) such as to increase the air-gap density by the ratio of E' to E.

The area of the final curve C which should be measured for the purpose of checking with the required area, is that comprised between the points on the armature surface which correspond with the position of the brushes on the commutator; portions of the flux curve measured below the datum line being considered negative, and deducted from the area measured above the datum line.

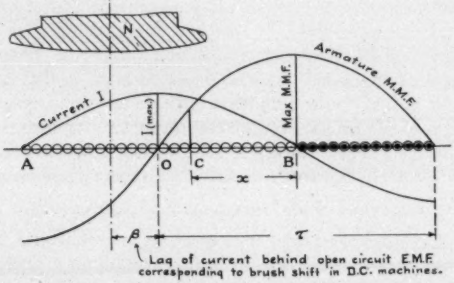
ARMATURE M.M.F. IN POLYPHASE GENERATORS.

In a continuous-current machine the current has the same value at all times in all the armature conductors, and equation (10) shows how the armature M.M.F. follows a straight-line law over a zone equal to the pole pitch, this being the distance between brushes referred to armature surface. In alternating-current and polyphase generators the curve of armature M.M.F. can no longer be represented graphically by straight lines as in Fig. 9, because the value of the current will not be the same in all the conductors included in the space of a pole pitch.

Considering first the polyphase synchronous generator, and assuming a sinusoidal current wave, it is an easy matter to draw a curve representing the armature M.M.F. at any particular instant of time, provided the phase displacement—or position of the conductors carrying the maximum current—relatively to centre line of pole is known. If this be done for different time values, a number of curves will be obtained, all consisting of straight lines of varying slopes, the length of which relatively to the pole pitch will depend on the number of phases for which the machine is wound. The average of all these curves will be

a sine curve, of which the position in space relatively to the poles is constant, and exactly 90 electrical space degrees behind the position of maximum current. This curve is most easily derived by assuming an infinite number of phases. Thus, the ordinates of curve I of Fig. 13 (assumed to be a sine curve) give the value of the current in the various conductors distributed over the armature surface. It is understood that the current in each individual conductor varies according to the simple harmonic law; but it is constant in value for a given position on the armature surface considered relatively to the poles. The direction of the current in the conductors between the points A and B may be

FIG. 13.



considered as being downward, while the direction of the current in the adjoining section of width τ would be upward. The maximum value of the armature M.M.F., therefore, occurs at the point B, its value being:

Maximum value of armature ampère-turns per pole = average value of current in section OB × number of turns.

$$= \frac{2}{\pi} I_{max} \times \frac{Z'}{2p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where Z′ stands for the total number of armature inductors, counting all phases. This may be compared directly with formula (11), which applies to direct-current machines, by putting it in the form

Max. M.M.F. (gilberts) per pole

$$= \frac{0.4\pi \times 2 \times I_c \sqrt{2} Z'}{\pi \times 2p}$$

$$= \frac{0.4\pi Z_c'}{1.11 \times 2p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

where I_c stands for the virtual or R.M.S. value of the current in the armature conductors.

That the armature M.M.F. curve in Fig. 13 is also a sine curve when the current follows the sine law is easily seen from the general solution, thus:

At any point on the armature surface, such as C (Fig. 13),

$$(SI)_C = \Sigma \text{ current} \times \text{turns}$$

$$= \sum_{x=OB}^{x=CB} (I_{max} \sin x) \times dx \times \text{Number of conductors per unit length}$$

If x is expressed in angular measure (radians), the conductors per unit x are,

$$\frac{\text{Number of conductors in space } \tau}{\pi} = \frac{Z'}{\pi p}$$

and

$$(SI)_C = \sum_{x=\frac{\pi}{2}}^{x=CB} I_{max} S \sin x \, dx \frac{Z'}{\pi p}$$

$$= I_{max} \times \frac{Z'}{\pi p} \cos (CB)$$

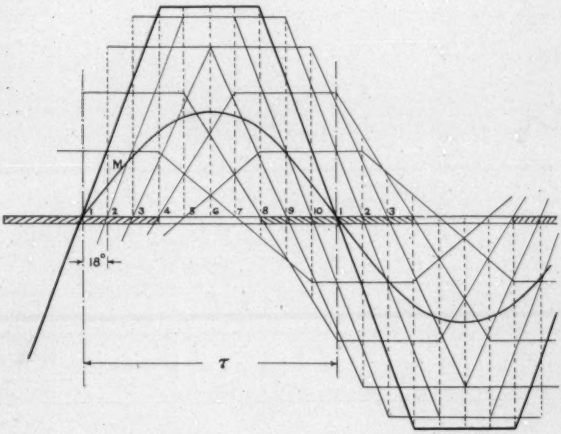
which agrees with the previously obtained maximum value of ampère-turns when the distance CB or x is equal to zero. The angle of displacement β (Fig. 13) of this curve relatively to centre line of pole depends upon the "internal" power factor, and also upon the displacement of the wave of developed E.M.F., a displacement or distortion which is due to cross magnetization. The angle β is not very easily predetermined, but, once known or assumed, the curve M can be drawn in the correct position relatively to the curve of field M.M.F.; and the resultant M.M.F. over the armature surface can be obtained exactly as for the direct-current machine (see Fig. 12).

ARMATURE M.M.F. CURVE OF SINGLE-PHASE ALTERNATOR.

When single-phase currents are taken from an armature winding, the M.M.F. due to this winding as a whole must necessarily be of zero value at the instant of time when the current is changing from its positive to its negative direction. This suggests that the magnetizing effect of the loaded armature on the field system will be pulsating; that is to say, it cannot be of constant strength at any given point considered relatively to the poles, whatever may be the phase displacement of the current relatively to the developed voltage. If the change of current in any given conductor be considered over a complete cycle, and if at the same

time the position of this conductor relatively to the poles be noted, it will be seen that, *relatively to the field magnet system*, the armature windings produce a pulsating field of double the normal frequency. The actual flux component due to the armature currents will not, however, pulsate to any appreciable extent, because the tendency to vary in strength at comparatively high frequencies is checked by the dampening effect of the field coils, even if the pole shoes and pole are laminated. It is, therefore, the average or resultant armature M.M.F. considered relatively

FIG. 14.



to the poles with which we are mainly concerned. The most satisfactory way of studying an effect of this kind is to draw the actual M.M.F. curves at definite intervals of time, and then average the values so obtained for different points on the armature surface, the position of these points being considered fixed relatively to the field poles.

This has been done in Fig. 14, where the windings are shown covering 60 per cent. of the armature surface, and the distance τ is one pole pitch. This distance is divided into 10 equal parts, each corresponding to 18 electrical degrees. The thick line represents the armature M.M.F. when the current has reached its

maximum value. The armature is then supposed to move 18 degrees to the right of this position, and a second M.M.F. curve is drawn, corresponding to this position of the windings. Its maximum ordinate is, of course, less than in the case of the first curve, because the current (which is supposed to follow the sine law) now has a smaller value. This process is repeated for the other positions of the coil throughout a complete cycle, and the resultant M.M.F. for any point in space (*i.e.*, relatively to the poles, considered stationary) is found by averaging the ordinates of the various M.M.F. curves at the point considered. In this manner the curve M of Fig. 14 is obtained. It will be found to be of a sine curve, of which the maximum ordinate is half the instantaneous maximum M.M.F. per pole of the single-phase winding, and it may be used exactly in the same way as the curve M in Fig. 13 (representing armature M.M.F. of a polyphase machine); that is to say, it can be combined with the field pole M.M.F. curve to obtain the resultant M.M.F. at armature surface from which can be derived the flux distribution curves under loaded conditions.

The maximum value of the resultant ampère-turns per pole is, therefore,

$$\tfrac{1}{2}I_{max.}\times\frac{Z}{2p}=I_{max}\times\frac{Z}{4p} \quad \ldots\ldots\ldots\ldots (14)$$

where Z is the total number of armature face conductors. Expressed in gilberts the formula is,

$$\left.\begin{array}{l}\text{Maximum ordinate of armature M.M.F. curve in single-phase alternator.}\end{array}\right\} = \frac{0.4\pi\sqrt{2}I_cZ}{2\times 2p}$$

$$=\frac{0.4\pi ZI_c}{\sqrt{2}\,2p} \quad \ldots\ldots\ldots\ldots (15)$$

which, together with formula (14), may be compared with the formulas (12) and (13) for polyphase generators.

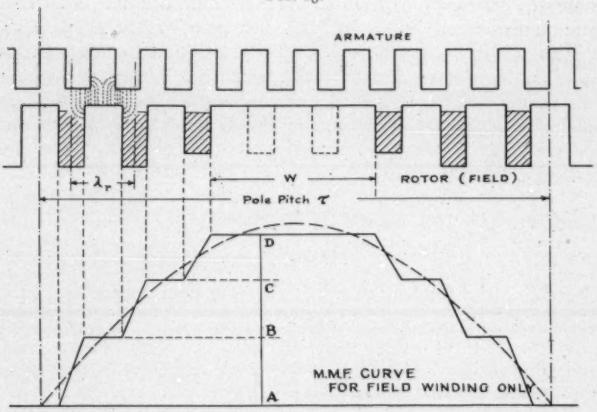
PREDETERMINATION OF FLUX CURVE IN HIGH-SPEED ALTERNATORS WITH DISTRIBUTED FIELD WINDING.

In the case of a slotted rotor carrying the field coils, and an air-gap of constant length—due to the fact that the bore of the stator or armature is concentric with the (cylindrical) rotor—the shape of the M.M.F. curve due to field excitation alone can

readily be found without resorting to the somewhat tedious process of getting the permeance between pole and armature points, as described and recommended for salient pole machines.

If the whole surface of the rotor is provided with equally spaced slots, the average permeance of the air-gap between stator and rotor will have a constant value for all points on the armature periphery. This condition is represented in Fig. 15, if the centre portion of the pole, of width W, is slotted as indicated by the dotted lines. This constant average air-gap permeance can be calculated within a close degree of approximation by making con-

FIG. 15.

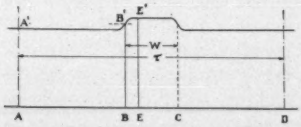


ventional assumptions in regard to the path of the magnetic lines, as was done in the case of the salient pole machines when deriving formula (1) giving the permeance at centre of pole. The flux lines can be supposed to be made up of straight lines and quadrants of circles; and if the permeance over one tooth pitch is worked out for different relative positions of field and armature, very satisfactory results can be obtained by this method. It will usually suffice to make the calculations for one tooth pitch in the position of greatest permeance, and again in the position of lowest permeance. The average of these calculated values, divided by the area of the tooth pitch in square centimetres, will

give the average value of the air-gap permeance per square centimetre.

Under this condition of constant air-gap permeance, the flux distribution on open circuit will follow the shape of the M.M.F. curve; but, in any case, since $B = M.M.F. \times$ Permeance per sq. cm., the flux curve can always be obtained when the M.M.F. distribution is known. Thus, if the portion W of the pole (Fig. 15) is not slotted, the permeance curve, instead of being a straight line of which the ordinates are of constant value, would be generally as shown in Fig. 16. From these values of the permeance per square centimetre of armature surface, curves such as those of Fig. 8 can be drawn, so as to include the reluctance of the armature teeth. From all points on the armature between A and B, and C and D (Fig. 16), the average air-gap permeance would have the value AA'. Over the central portion W it would have the value EE', while, in the neighborhood of the points B and C, it may be assumed to have an intermediate value as indicated by the ordinate BB'.

FIG. 16.



If the depth of the slots in the rotor has been decided upon and the number of ampère-conductors in each slot determined, the distribution of M.M.F. over armature surface due to the field winding can readily be plotted as in the lower sketch of Fig. 15. Thus the ampère-turns in the coil nearest the neutral zone are represented by the height AB, those in the middle coil by BC, and those in the smallest coil by CD. The broken straight line so obtained is best replaced by the dotted curve, which takes care of fringing, and represents the average effect. This curve, being the open-circuit distribution of M.M.F. over armature surface for a given value of exciting current, may be combined with the curve of armature M.M.F. to obtain the resultant M.M.F. under loaded conditions. The flux curves A and B for open-circuit and loaded conditions can, therefore, be derived by proceeding exactly as in the case of the salient pole designs.

With salient pole machines variations in the open-circuit flux distribution can be obtained only by shaping the pole shoes so as to alter the air-gap over the pole pitch in a manner which is not easily determined except by trial, but with the field winding distributed in slots it is not difficult to arrange the coils to give any desired distribution of M.M.F. over the pole pitch. Thus, if the desired flux curve is known (a sinusoidal distribution is usually best for alternating-current machines), and if the average permeance per square centimetre of the air-gap has been calculated, an ideal M.M.F. curve can easily be drawn, since, at every point, the M.M.F. is the ratio of the flux density to the permeance per square centimetre. The spacing and depth of slots can then be arranged to produce a magnetizing effect as nearly as possible the same as that of the ideal curve.

CONCLUDING REMARKS.

A study of the flux distribution in dynamo-electric machines, by plotting curves as outlined above, appears to the writer to offer many advantages, of which a clearer conception of the fundamental physical phenomena is by no means one of the least important. In continuous-current machines it is an aid to the study of commutation troubles, and, since the maximum value of the flux density can be determined, the maximum voltage between commutator segments under different conditions of loading can be calculated. In alternating-current machines it leads directly to the determination of wave shapes under various conditions of running, and it should be very helpful in designing machines to give as nearly as possible a sine wave E.M.F. at all loads. The usual text-book conception of demagnetizing and cross-magnetizing ampère-turns as distinct components of the armature M.M.F., capable of being separated and treated vectorially, is abandoned, and the reaction of armature on field is dealt with more scientifically because the saturation of the teeth and the effect of high densities in limiting the amount of distortion are considered. The chief advantage, however, lies—as previously mentioned—in the fact that new types of machines, or radical departures from existing types, can be designed, and their performance predicted, without reference to empirical formulas or test data, the application of which would be a difficult matter for the designer, whose experience and judgment might, indeed, be unequal to the occasion.

ARTISTIC PAINTING AND THE OLD MASTERS.*

BY

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THAT between the fourteenth and the seventeenth centuries artistic painters possessed secrets which account for the permanency of their paintings, and that the manufacture of pigments for artistic painting is a lost art and for that reason no modern painting can be considered permanent, is the general impression throughout the world to-day.

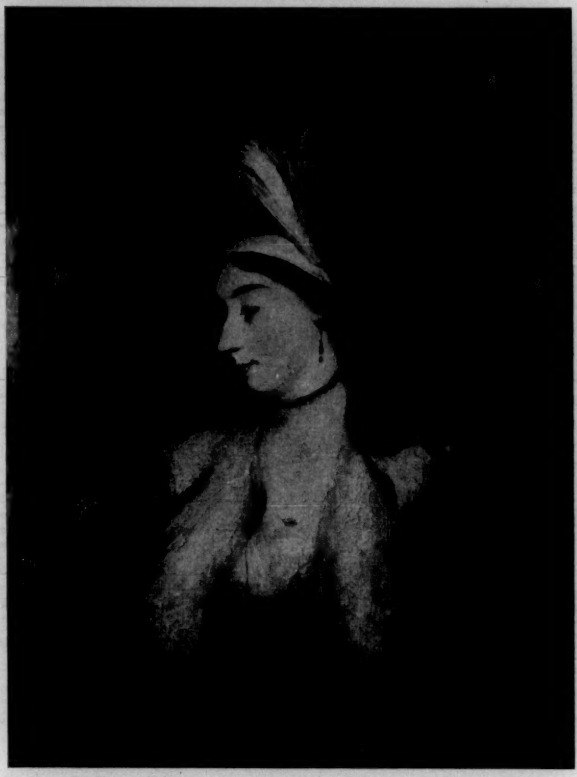
The first artistic oil painting of which there is any record was executed in the year 1399 by Hubert Van Eyck, a Dutchman, and it was to him and his brother, Jan, that the credit is given for having invented or originated oil paintings. This may or may not be a fact, for there are records indicating that decorative oil painting was applied in the eleventh and twelfth centuries in England, and invoices rendered for such work are also in existence. However, painting with oil to produce artistic results was, without doubt, no sudden discovery, but was a gradual development, and only as improvements in it were made from time to time was there attained any degree of perfection.

Much has been written on the subject of the secret of the old masters, which was supposed to consist in the use of pigments which have never been imitated, and of vehicles or oil media with the composition of which we are at the present day still unfamiliar. The belief in this secret was very marked in the middle of the eighteenth century, and, in fact, many artistic painters themselves held the opinion that the Dutch and Italian artists were possessed of a profound secret. Sir Joshua Reynolds gave much credence to the myth—for myth it was—and kept copious notes on the subject, and he himself was in continual search of the secret.

Sir Joshua Reynolds, a most remarkable painter and as good a portrait painter as ever lived, was, unfortunately, very impractical and comparatively ignorant, and did not possess the remotest idea

* Presented at the meeting of the Section of Physics and Chemistry, held Thursday, November 5, 1914.

of how to confirm by experiments whether the secrets that he was continually discovering possessed any value or not. Sir Joshua



The Metropolitan Museum of Art

Painting by Sir Joshua Reynolds in which the face has bleached practically into a monotone, due to the fact that incompatible pigments were used. The dress and turban and background are still in excellent condition, and evidently were painted by one of his students.

was a most prolific painter, executing throughout the three busiest years of his life an average of three finished portraits a week.

He was well known in London in his day, and was just as popular then as Edison is now. He was invited to every function, public or private, and had he attended he would have had no time left

This is one of the most striking examples of the decomposition of Sir Joshua Reynolds's paintings, and the photograph is even better than the original. The original is practically of a "putty" color, and the line of demarcation of the lips shows up better in the photograph, for certain photochemical reasons, than is portrayed in the original. This is undoubtedly due to the mixture of an organic lake with one of the metallic pigments in the experiments of Sir Joshua Reynolds.

for his work. He had a number of students, many of whom possessed great ability, and it is said on excellent authority that of every person who came to him for his or her portrait (and it

was the fashion in those days to have a Reynolds portrait made) he himself painted the face and the hands only, leaving the background and dress to be done by his pupils. Indeed, had he painted

The Metropolitan Museum of Art

Painting of the portrait of an infant by Sir Joshua Reynolds, in which even the red of the lips has faded, and the painting now appears as if it were painted in two colors.

the entire portrait, it would have been physically impossible for him to have painted three a week, and the further fact that his students did paint the background and the dress is undoubtedly the reason that at this very day many of his beautiful pictures

which have faded are still perfect in these particulars. There are some of his pictures—and I have in mind three of them in the Museum of New York—in which the face and the hands have bleached out, and practically nothing is left but a smudge. This is probably due to the fact that every time Sir Joshua was on the verge of discovering the supposed secret of the old masters he tried it on the first sitter that came in, and invariably it failed.

The well-known picture of "The Smoker," by Frans Hals, in which it is plainly evident that the red of the cheeks and the red of the lips on which madder lake was used was painted over the bottom color after the bottom color was thoroughly dry.

Frans Hals was the first impressionistic painter, and, as he used brushes with handles six feet long, all his paintings look their best at a distance of more than six feet.

Just as careless as was Sir Joshua in his experimental work or in trying out mixtures with results he had no notion of, so careless was he in copying likenesses, and the result was that hundreds of pictures were thrown back on his hands and were sold after his death. Of course, there are many of his works still in existence which are very good and are fairly preserved.

One of the peculiar practices of Reynolds was to mix a lake color with an earth color, when the two were incompatible. Now it happens that a flesh tint can be produced, and has been produced from time immemorial, by a mixture of an earth known as yellow ochre, a little white pigment, and madder lake. Each of these three by itself is permanent, but when mixed each one undergoes a very slow chemical decomposition. This decomposition produces a change of color, as is well illustrated in the case of yellow ochre and madder lake mixed together; when first mixed the result is a bright flesh color, but in six months the color has changed to a sickly, pale, ghastly mud color.

Two centuries before Reynolds, Frans Hals, than whom, perhaps, no better portrait painter ever lived, was well aware of the incompatibility of colors, and his wonderful Flemish characters, with their red cheeks and redder noses, are still as lifelike to-day as they were three hundred years ago. This was because Hals carefully allowed one color to dry before he put another over it, and he also used the so-called permanent madder lake as a glazing color to produce his effects.

Another potent factor in the permanency of the older paintings is that the early Italian and Flemish painters had possibly eight or nine pigments only. To-day there are over two hundred pigments, but no painter need be fearful about the permanency of his colors if he will use only those which are known not to interact.

Madder lake has a very interesting history. There is every reason to believe that the Egyptians used it, and that madder constituted their red dye. The color is extracted from the roots of a plant called the *Rubia tinctorum*. It has been known for generations that if this plant is boiled with a solution of alum a red coloring matter develops and the alum fastens it. In the South of France cultivation of this plant became a great industry, and in order to encourage it the French Government decreed that the trousers of all the French military uniforms should be dyed red with madder lake, and that is why to this very day the soldiers of the French army wear bright red trousers. A peculiar point in this connection of the development of the madder industry is that thirty years ago a method of making madder lake synthetically was discovered in Germany. The product was made from coal tar and is known as alizarine, and for more than twenty years the French Government used this product in place of the genuine madder

lake, and the cultivation of the madder root has become almost a lost art.

Up to about fifteen years ago the usual method employed by experts in judging whether paintings were real or spurious was the "subconscious" method. This is the same method we all use when, say, we receive a letter written by a person of our acquaintance with whose handwriting we are thoroughly familiar. By the subconscious characteristics of the writing we can judge the genuineness of the letter, as there are very few, if any, people who write absolutely alike; and so when a picture is put before an expert he tells by the same instinct whether it is genuine or not. Within the last ten or fifteen years, however, the identification of pictures by more scientific methods has been practised. Some experts, in employing these methods, make microscopic analyses of pigments, and others—one in particular, Professor Laurie, of Edinburgh—photograph sections of paintings with a microscope, and then compare the enlarged detail of brush work of the picture under inspection with that of one of known origin. There are clever paint imitators who can paint pictures which are so closely like the original that the "subconscious" method is of no avail in detecting them and the scientific investigator must always be consulted. Thousands of spurious paintings, copies of the late masters and copies of the modern ones, which have been passed as genuine, and which have been sold for enormous amounts, are in existence. All works of art are imitated in the same way, and the identification of a spurious piece of work is sometimes difficult. We find furniture imitated to perfection; we find ancient pottery and bronzes, old weapons and brass work so completely simulated that experts are frequently baffled. Sheraton furniture is a familiar example. Sheraton had a little shop and did most of his work himself, but occasionally employed a few expert artisans to help him. The amount of so-called genuine Sheraton furniture in existence is so great, however, that Sheraton would have had to employ a thousand men in a factory covering several acres if he had made all the furniture which is supposed to be genuine Sheraton.

Rembrandt lived for sixty-three years, and for forty-five years was active as a painter. So far as is known, some seven hundred pictures were painted by him, and yet I have made an estimate, which is probably incorrect, that there are fully be-

tween four and five thousand pictures in existence, for all of which great prices have been paid, and all supposed to be genuine Rembrandts.

Peter Paul Rubens, who was born in 1577 and died in 1640, spent over forty years of his life painting, and some of his pictures took fully a year, because they are so perfect in detail, so large, and so carefully executed. There is no doubt that many of his pictures were partly painted by him and partly by his scholars, and yet it would have been absolutely impossible for any human being to have painted all the Rubens that there are in existence. In fact, this may be said of every great painter, modern or ancient.

There was an auction sale last year in the city of New York, at the Plaza Hotel, at which some of the best works of George Inness were sold. One particularly fine piece which had already been on exhibition, and the origin of which no one doubted, was placed on sale; but as it was about to be sold the son of the famous painter had it withdrawn, stating that he was familiar with every painting made by his father, and he believed the one about to be sold to be an imitation.

Some picture dealers whose reputation is questionable have peculiar and remarkable methods for marketing their spurious wares. Of course, many have been discovered, but very few of them have been prosecuted. One in particular was caught in a very novel manner. He possessed a most excellent picture painted on a panel, and this he offered to a collector at a ridiculously low price. After the purchase the dealer asked the buyer to write his name on the back of the panel so that he would be sure of getting his purchase and no other picture. When the purchaser received his picture he found his own handwriting on the back of it. Being somewhat skeptical, however, he felt that the picture sent to him was not the one he had bought. He waited for six months and then sent a friend to this dealer, and the latter brought out the (very) picture which he himself was supposed to have originally purchased. The dealer made the same request for the buyer's signature. The second purchaser wrote his name on the back of the picture, paid for it, but insisted on taking it with him. The second picture was later examined very carefully and was found to consist of a genuine on top and an imitation beneath, the latter being painted on a thinner panel. The second buyer

had written his name on the imitation, and it developed the first had done the same.

An interesting case happened in London only a few years ago, showing how good imitations can be sold and stamped as genuine through fraud and chicanery. There was a painter in London who was a most clever imitator, and who copied a large number of the old Dutch and the semi-modern English painters. A dealer called at his studio and offered to buy his entire works on condition that he himself should leave the country. The sum offered was sufficiently inducive, and the painter sold all the imitation masterpieces he had and went abroad. Thereupon the dealer, in connivance with a lawyer, conceived a unique scheme for placing these pictures on the market. The lawyer attempted to serve a summons on the artist to recover an amount of money ostensibly loaned on these paintings, and, finding his studio closed, applied to the court for permission to enter it and sell at auction all the effects found therein. After due service of the summons by publication, the court issued an order that the effects of the defendant be sold at public auction, describing in detail all the spurious masterpieces as supposedly genuine paintings, and thereupon all the effects of the defendant were taken to a very prominent auction room in London and placed on sale. There was outwardly no question as to whether the paintings were genuine, because the Supreme Court, in issuing judgment, had stated that the effects consisted of "four Rubens, three Reynolds, and one Gainsborough, and a large number of other prominent and well-known masterpieces." The auction sale created at the time a great deal of interest in London because there had never been offered for sale at any one time such a large number of masterpieces. The amount which the lawyer and the dealer realized was enormous, and to this very day those who purchased these pictures would probably never have discovered the fraud if the artist himself had not read of the sale and felt it his duty to come back and expose the whole matter.

As regards the scientific methods of determining the originality of paintings, I have mentioned the method devised by Professor Laurie, of Heriot-Watt College, which consists in a photomicrographic method. Professor Laurie analyzes the brush work of a known masterpiece and compares it with the one in question, and the analogy of the strokes indicates the genuineness. There is

another method, which I can best describe by relating a case in which two pictures were in dispute and the case was settled purely on scientific grounds. A well-known collector in New York bought a small picture by Rembrandt for $15,000, and all who saw the picture agreed that it was genuine. The collector felt, however, that he was paying too much for the picture, as it was in rather poor condition and not a very good example. The dealer thereupon offered in addition a very excellent Ruysdael, which was dated 1650, and was in fine condition. Ruysdael was a Dutch landscape painter, and one of the first prominent of such. Three hundred years ago, for every landscape painted there were probably one thousand portraits painted, and this painter is known for his excellent scenery. A number of prominent experts viewed this Ruysdael, and they all agreed, according to the "subconscious" method, that it was not genuine. The dealer protested, and, as a matter of fact, it was very difficult to prove whether it was genuine or not, for if it was spurious it was reasonable to infer that the Rembrandt was also spurious, although that, too, was very difficult to prove. As a last resort a scientific expert was engaged, who removed from the face of the painting three small pieces hardly larger than the eye of a needle, and from the back of the picture a small section of the oak panel on which it was painted. After a week he reported to this effect:

"This painting is an imitation, but it is probably between fifty and seventy-five years old, for the following reasons:

"1. The white pigment used in the sky is made of zinc oxide and not of flake white. Three hundred years ago zinc white was not known, and the Flemish painters used flake white.

"2. In the shadows the bitumen used is still transparent. Bitumen three hundred years old is converted by light into carbon, and becomes insoluble.

"3. A microscopic section of the wood on which the picture is painted shows that the protoplasm or 'living matter' in the cells has not entirely dried out. Wood which is three hundred years old shows no such protoplasm.

"4. I therefore pronounce this painting an imitation for the above-mentioned reasons."

The dealer then acknowledged the Ruysdael was an imitation.

One of the reasons that the ancient paintings have lasted so long as compared with some of the modern is the fact that the

condition of the atmosphere in a modern city is so totally different now from what it was prior to the invention of some of our modern conveniences. For instance, in the city of New York the air contains a perceptible amount of sulphuric acid, due to the burning of hard coal. In the city of Pittsburgh and in the city of London the air contains other acids, and coal dust in addition. The influences of coal gas and the products obtained from burning illuminating gas are sufficient to have a serious effect on paintings. Then, again, light and darkness are important factors in the preservation of pictures. Light bleaches and darkness blackens, and a painting which remains in a dark corner for six months turns yellow wherever oil or an oil varnish was used on it.

In restoring paintings one of the simplest methods and one of the most efficient is, after wiping them free from dust and dirt, to place them in the bright sunlight for two or three days, and the sunlight will bring back the colors, excepting such modern lake colors as are faded by the sun, in all their pristine glories.

Another destructive agent to paintings in homes is the gases derived from the cooking of vegetables. Certain vegetables contain a large amount of sulphur, which is easily liberated, particularly in the presence of vinegar, and this sulphur affects colors, particularly those containing white lead, lead pigments, and others. To a very large degree varnishing preserves paintings from the influence of gases, but, of course, the varnish used must not be made with a drier which contains any chemical affected itself by gases.

I mentioned already the interaction of one color on another. Ultramarine blue, which is perfectly permanent by itself, when mixed with flake white and subjected to the influence of an acid gas changes in color from a sky blue to a dirty brown. This mixing of compatible colors is another reason for the deterioration of paintings, and one or two examples will suffice to indicate to you why paintings deteriorate. The modern schools, like the Cubists for style and the Impasto for technic, are very unfortunate. As regards artistic style I have nothing to say, because that is another subject; but the Impasto is the method used by many painters in which they pile up pigments until the painting itself is plastic to a certain degree. In other words, bushy eyebrows are not portrayed so much by light and shadow effect as by piling up paint on the eyebrows until a really plastic form is

produced. If painters of three and four hundred years ago did this, nothing is known of it, because there are no paintings of that time in existence which were painted by this method, for the obvious reason that they could not have been permanent; and, therefore, painters of to-day ought to be warned against this method of piling up paint, because within twenty or thirty years a painting of this type will consist of dried-out pigment, which will fall off the canvas by its own weight. I have seen modern impressionistic painters who piled on their flat colors with a mottled effect, and in less than two years the paint dropped from the canvas; it can therefore be recommended that every painter use simple pigments, simple oils, and not too copious an application of paint. Where glazed effects are desired, the best results are obtained when one coat is applied over the other coat after the first is thoroughly dry and hard. All the newer media which give quicker and better results may be useful when applied to paintings to be used for making illustrations in colors only, but if the painting is to be permanent and is intended as a work of art for future generations, the best materials to employ are simple pigments and linseed oil. As an illustration of this, the great French painter, Vibert, with whose paintings, particularly "The Schism," every one is familiar, devised the idea that a resin similar to ordinary resin and a volatile liquid like gasoline or benzene would make a most excellent medium, for it would dry quickly, the colors would be permanent, and the oil itself would have no chemical action on the pigments. Theoretically this is true, but practically it proved a failure in time, and this excellent painter did not live to see the decomposition of his own works. A few months ago I viewed Vibert's excellent painting "The Schism" at the National Gallery in Washington, and I asked the curator of the gallery whether he knew that this excellent example of Vibert, for which I think the National Museum paid a large sum, was beginning to decompose and the pigment was leaving the wood on which it was painted. This is actually the case, but I hope some one will be able to devise a method whereby this excellent picture will be preserved. As it is now, the surface is badly pitted, and in a few years the paint will drop off almost entirely.

RECENT DEVELOPMENTS IN CAST-IRON MANUFACTURE.*

BY

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FOUNDING is one of the early arts and undoubtedly had its origin at the time of the development of the blast furnace in the latter middle ages. It has made its greatest progress, however, since the methods of using mineral fuel in this furnace have cheapened the product of the latter so much that ninety per cent. or more of that product is now nothing more than the raw material for the production of steel. The art of founding was almost ignored by the scientific metallurgist until within comparatively few years. The developments in the manufacture of steel were so rapid and of such vast importance to the whole of mankind that practically all the labors of iron and steel metallurgists were devoted to steel, and the foundryman was left to struggle along as best he could on the basis of his hard-earned, and sometimes contradictory, practical knowledge and experience. In the nineties of the last century was brought about a great change in this condition, for chemistry began to be applied freely in the foundry, and by its aid many facts in connection with its manufacture of cast iron were brought out. Some of these facts the practical men declared were not true, and the conditions of cast-iron manufacture are so complex that many are still in dispute.

In 1900, the closing year of the decade referred to, I published in the *American Machinist* an article in which, to my mind, was made the first definite and coherent statement of the nature of cast iron, particularly in its relation to steel. The following are some quotations from this article:

> . . . the key to the subject lies in considering cast iron and steel not as entirely separate and distinct, but as the same substance, passing by infinitesimal gradations from the chemical and physical properties of one extreme to those of the other. The probable reason that this fact is not more

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widely realized than it is, is that both of the extreme conditions are "soft"—soft gray iron and soft or mild steel—while the connecting link between them is the hardest of tool steel at one end and the hardest of white iron at the other, with no sharp lines separating them from one another.

There is no doubt that there could be made in a blast furnace, from the proper materials, an iron containing silicon 0.2, manganese 0.4, phosphorus 0.03, sulphur 0.03, combined carbon 2.75 per cent., graphitic carbon, trace.

But excessively hard crucible steel may be made having precisely the same analysis, and both have practically the same properties. The crucible steel is so hard and brittle that it cannot be commercially rolled or hammered, and is of no value, as well as being extremely difficult to make, while the greatest care and effort, and probably several weeks or even months of trial, would be necessary to produce an iron with the composition given, in a blast furnace, and when produced it would be of little commercial value; so that a material having this composition is seldom or never produced—never commercially—and we are not, therefore, familiar with it, and do not realize the fact, which it is impossible to emphasize too strongly in this connection, that it exists, or may exist, and constitutes a perfect link between cast iron and steel.

Since soft iron contains the most total carbon (about 4 per cent.) and very mild steel the least (say, 0.06 per cent.), while the intermediate stage, the very hard iron or steel just described, contains about the average of these two, roughly speaking, and is so much harder than either as not to resemble them in its properties, this may be thought to weaken or invalidate the above statement; but it does not, when properly considered, for, while the total carbon is high in the cast iron, almost all of it is in the graphitic form and only a trace is combined.

If we say, "Cast iron and steel are alloys of the chemical element iron with carbon, with a chemical and physical admixture of other compounds, and the hardness of the alloy depends, within commercial limits, upon the amount of the carbon in it, while its tenacity, ductility, and other physical properties depend upon the other substances present, and upon the physical treatment it receives, and the variations produced by these are approximately the same in both," we shall have a blanket definition of the two substances which covers both quite fully and with substantial accuracy.

Too much stress can hardly be laid upon the two kinds of carbon in cast iron, the "combined" being chemically united or combined with the iron to form a chemical compound; the other, the graphitic, being merely interspersed among the grains or crystals of the iron. The most striking proof of this latter is that shown a few years ago, I have forgotten by whom, which consists in brushing with a steel-wire brush the fractured face of a pig of gray iron, one-half of which is protected from the action of the brush; the brushed half becomes perfectly white, like white iron, although the grain, of course, remains as before. The unbrushed half, of course, shows the contrast more plainly.

Iron, when hot, has a far higher capacity for dissolving carbon and retaining it in combination than it has when cold. The graphitic carbon is probably all in solution at first, although this is not certain. But as the iron

cools, if it cools slowly, the graphite is forced out and what is near the surface flies off into the air. It can be seen doing it at a blast-furnace cast when the iron is of the proper composition. The rest is retained, immeshed in the grains of the iron, and probably gives to gray cast iron whatever toughness and flexibility it possesses, separating the grains or crystals from continuous contact and lubricating their movements.

Thus hard cast iron, while much less flexible, is much more elastic than soft, as it should be, having much less graphitic carbon in it. The more slowly the iron cools the more graphite crystallizes out of it and the larger the crystals, so that comparatively hard iron, when cast into large masses and allowed to cool for several days, or longer, will show a grain which would put "No. 1 X" to the blush.

. . . . . .

The tendency to eject carbon and become softer, in consequence, does not by any means stop when the iron is solid, nor until it is down to the lower limit of the red heat at least, and how much lower the writer will not undertake to say. When any casting was made from moderately hard iron which it was required to machine, it was always kept carefully covered up until dead cold, and this was known by experience to be very necessary. Some intentionally "chilled" pieces, when made of very hard iron, would "fly" off themselves from the cooling strains set up, but could often be saved by keeping them hot as long as possible.

When the iron is cooled suddenly, the carbon does not have time to separate out, and remains combined with the iron, making it "white" instead of gray, because of the absence of the black graphite.

I think that this is a reasonably good presentation in a broad way of our knowledge of the subject to-day. It is a matter of interest that, in the subsequent part of the above article, is to be found the statement that the only reason for the use of charcoal iron, particularly for chilling purposes, was that, charcoal being free from sulphur, iron as low in silicon as desired could be produced in the charcoal furnace without any important simultaneous increase in the sulphur above that in high silicon iron, which could not be done in coke furnaces until shortly before that time, but that it could be done then at will, and that charcoal iron had accordingly no advantage over coke iron, and was destined to pass out of use. This is probably as good an illustration of assuming that all the facts fit an incomplete theory and drawing a totally erroneous conclusion in consequence as you will find anywhere in technical literature, and it is my particular purpose to point out the important respect in which charcoal iron differs fundamentally from coke iron, and to describe the method by which we have succeeded in obtaining, for a modified form of coke iron, the advantages of charcoal iron in a greater degree than are obtainable by it.

In 1901, the year following the publication of my article, Professor Henry M. Howe read a paper before the American Institute of Mining Engineers, in which the theorem of the continuity of the cast iron-steel series was set forth more elaborately and in far better language than in mine. Professor Howe pointed out that the important question in regard to the carbon in cast iron is not what is the total carbon, nor yet how much is thrown out as graphitic, but how much is *left combined,* because it is upon the quantity of combined carbon in the matrix that its strength depends.

It seemed to me at first that this statement put the matter in a nutshell, and was obviously correct. It will be seen later that Professor Howe's is also an incomplete theory, and that certain other factors enter in of so much greater importance in the final result as almost to eclipse the truth contained in his statement taken by itself.

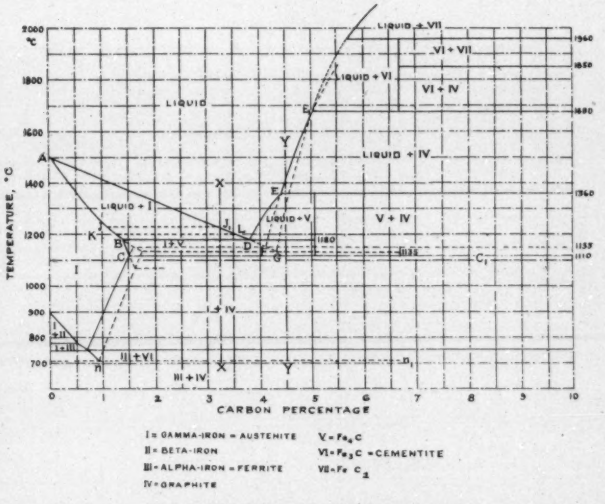
From the quotations I have made, it is obvious that cast iron must be considered primarily as an alloy of iron and carbon. This is quite proper in a more elementary sense, because carbon is present in iron quantitatively to a greater extent by weight and to a far greater by volume than is any other element. Carbon has, moreover, a more powerful effect, weight for weight, than any other element except one.

THE IRON-CARBON DIAGRAM.

The Iron-Carbon Diagram, as applied to cast iron by Guertler based upon researches of Wittorff, is shown in Fig. 1. In Fig. 2 is shown a similar diagram drawn by Upton. Both of these have been obtained through the kindness of Professor William Campbell, of Columbia University. You are all probably familiar with the general form of these diagrams. The abscissas represent percentages of carbon, and the ordinates temperatures. The diagram, within its range, attempts to set forth the changes which occur in any solution of iron and carbon. A horizontal line runs across at the temperature of 1180° C., and two diagonals drawn respectively from the upper right- and left-hand portions meet upon this line at the point corresponding to 4.2 per cent. of carbon in Upton's diagram, at 3.8 per cent. in Guertler's. The diagrams attempt to show not only equilibrium conditions,—that is to say, those conditions which prevail after the mass has been

allowed sufficient time in cooling to reach a complete state of equilibrium,—but also metastable conditions. The interpretation of certain of the transformations is extremely difficult. I will not try at this point to make an exposition of the complete diagram, but will only call attention to its salient features. Considering Guertler's diagram and starting with a molten solution above the diagonal line on the left-hand side, we have a homogeneous solution—let us assume one whose composition is represented by the

FIG. 1.

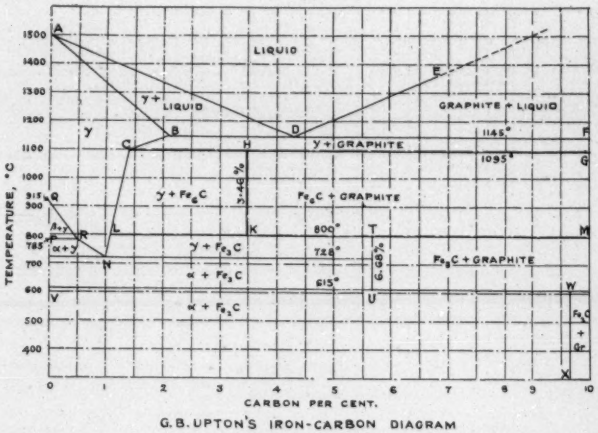


GUERTLER'S IRON-CARBON DIAGRAM

line XX. When the temperature falls, the composition remains constant until point A is reached, when, if ample time be allowed for the cooling, a solid freezes out, whose composition at any temperature is given by the intersection of the horizontal through that temperature with the line AB, in the present instance the line JJ_1, shown on the diagram. The metal represented by the point J obviously contains less carbon than that of the whole mass represented by the abscissa of the line XX, and the carbon rejected by

this solution in freezing must go over into the remainder of the solution, and so increase its carbon. If sufficient time is not allowed in cooling through any range, for instance that from JJ_1 to KL, the carbon from the solution is not able to diffuse into the solid and bring the percentage up to that represented by the point K, but tends more to follow the vertical line from J to K. This takes less carbon from the solution and leaves the excess in it greater. We have, therefore, the curious condition that the more rapid the cooling the greater the difference in carbon contents of the first and last frozen portions of the original metal.

FIG. 2.



G. B. UPTON'S IRON-CARBON DIAGRAM

After the metal has fallen in temperature below the line BD, it is entirely solid, but is not yet in its permanent condition, because carbon tends continually to fall out of solution. The method by which this takes place is subject to various conditions, and is not yet fully understood, even among the scientists who deal with this phase of the subject, as will be clearly seen by the difference between the lower portions of Fig. 1 and Fig. 2, which are intended to represent the same set of objective phenomena.

The following brief statement of the possibilities in regard to the transformation of these points is quoted from my reply to the

discussion of my paper, "The Effect of Oxygen, etc.," before the Institute of Mining Engineers, published in its *Bulletin*, June, 1914, and was prepared for me by Professor Campbell, through whose kindness I am able to present here three possibilities based on the work of Guertler (who founds his conclusions upon the experiments of Wittorff and Ruff) and one based on Upton's iron-carbon diagram. According to Guertler:

I. In the stable condition above 1360° C. and 4.4 per cent. C., we can have liquid + graphite.

At 1360° C. the reaction occurs; liquid + graphite = Fe_4C, and in alloys with 4.4 per cent. carbon down to 3.8 per cent. we find Fe_4C crystallizing out from the melt.

At 1180° C. we have the eutectic of austenite + Fe_4C.

At 1110° C. Fe_4C breaks up into austenite + graphite.

At 750° C. the eutectoid of ferrite and graphite forms.

These are equilibrium conditions which are reached only with extremely slow cooling.

II. With more rapid cooling, the reaction at 1360° C. does not occur. Graphite separates from the melt, and at 1155° C. we get the eutectic of austenite + graphite.

III. With more rapid cooling, Fe_3C separates out from the melt and at 1135° C. and 4.3 per cent. carbon forms a eutectic with austenite; then at 710° C. we have the eutectoid Fe_3C + ferrite, commonly known as pearlite.

According to Upton's diagram, white irons are super-saturated solid solutions which are breaking down; and the stable constituents are austenite + graphite above 1095° C.; austenite + Fe_6C or Fe_6C + graphite below 1095° C.; and at 800° C. Fe_3C appears while Fe_8C disappears. At 600° C. F_3C breaks down into Fe_2C. Fe_6C and Fe_2C have yet to be distinguished from Fe_3C under the microscope.

Leaving this for the present, let us consider the conditions represented by an iron-carbon alloy, containing more carbon than that represented by the point D on both diagrams. Assume, for instance, iron of a composition represented by the line YY. According to both diagrams, when the temperature has fallen to the point where line YY cuts the right-hand branch of the curve solidification begins; but in this case it is either Fe_4C, graphite, or Fe_3C which is thrown out of solution.

The relationships expressed by the dotted lines FE and GE_1 are too obscure for description at this point, though we may revert to these briefly after examining the action of a few of that infinite variety of alloys answering to the comprehensive name of "cast iron."

In either case, it is well to remember that, when the temperature falls slowly, the iron tends to follow the one or the other of the branches of the curve in cooling. If a hypoeutectic iron,—that is, one lying to the left-hand side of the point D (for instance, the composition represented by the line XX),—selective freezing tends to take place along the line AB, with a resulting concentration of carbon in the mother liquor, represented by the distance between the lines AB and AD on the horizontal line corresponding to the given temperature. But if sufficient time be not allowed, then the iron tends to freeze in a purer (that is, lower carbon) condition, with a greater enrichment in this element of the mother liquor.

On the other side of the eutectic point D the hypereutectic iron tends in freezing to follow along one of the lines DE, FE, or GE_1, and in any event this corresponds to the falling out of graphite, or a carbide which, being richer in pure carbon, leads to a direct proportional impoverishment of the mother liquor; and this impoverishment in this case is greater if time is allowed for full equilibrium to be reached, and less if this time is shortened.

When the whole mass has solidified, it is at the temperature represented by the points D, F or G, and consists of a mixture of different constituents, and the character of this mixture depends upon the original composition of the iron-carbon alloy and its rate of cooling from its initial temperature to that of the freezing point. This mixture generally contains graphite physically enmeshed, if it be a hypereutectic iron.

Below the line CC_1 it is obvious, from the diagrams, that their

authors disagree considerably as to the details of the action, but further graphitization goes on, and the solution of pure iron in cementite becomes poorer and poorer in carbon until the line nn_1 is reached, when a very important transformation takes place. All the solid solution remaining breaks up into pure cementite in all detached areas and into pearlite, one of the best known constituents of all irons and steels, and one which can perhaps best be described by reference to the fact that 0.9 carbon steel, in its unhardened condition, consists entirely of this material. Pearlite is well known as one of the strongest and toughest of the countless combinations of iron and carbon.

Even at this low temperature, 725° C. or 1337° F., barely a dull red, the iron is not yet in equilibrium. The cementite may break down to pure iron and graphite in relatively large masses. Pure iron or ferrite is only about one-third as strong as pearlite, and, of course, when its continuity is broken up by graphite it is thereby further weakened, and, being in large areas, its effect in weakening the whole structure is very great.

The line *DE* of Upton's diagram may be entirely disregarded, since it is well known that the actual line is much steeper and is probably, nearly if not exactly, as drawn on Guertler's diagram, which is more recent than that of Upton and is based on the researches of Wittorff, the most recent and probably the most accurate of any of the investigations on high-carbon alloys of iron.

Upton's diagram is shown principally for the reason that it contains the vertical line *HK*, since it has been found by actual experience that irons with more than a certain quantity of carbon graphitize to a much greater extent than similar irons containing less carbon, and that high carbon irons not only throw out more graphite than do lower carbon ones, but the combined carbon remaining is very materially less in the high carbon irons than it is in the low. The line *HK* indicates such an action, and is, therefore, to some extent in agreement with the observed facts, although I am quite unable to state whether the exact location of the line at 3.46 per cent. carbon is correct.

From the point of view of practical value, two possibilities according to these diagrams stand forth prominently.

1. Graphite can separate directly from the melt. This is contrary to the claims of Professor Howe and Professor Sauveur, but is abundantly supported by the facts. Their contention that

this action can take place only through the prior formation of cementite is completely negatived by facts of practice which are matters of common knowledge to furnacemen.

2. After solidification, according to Guertler and Upton, in certain areas of the diagram a very slight change in conditions may cause a complete change in the resulting product.

The iron-carbon diagram gives graphically the best information we have concerning the action of alloys of pure iron and carbon, but cast iron is far removed from that theoretical material, as it contains, in addition, silicon, sulphur, phosphorus, manganese, and sometimes oxygen, generally, if not always, in vastly varying quantities. There may be also titanium, vanadium, chromium, and nickel and perhaps many other elements present, but the first five are the important ones in commercial pig irons. Each of these exercises its principal action upon the carbon and upon its condition, and as a result we would need in practice a complete diagram of the form given for each. To represent graphically, for instance, the effect of carbon and silicon together, we would require a figure of three dimensions, or, in other words, a solid or "glyptic model." In addition, for each percentage of each of the other elements there would be a variation of this model to express all the facts. The effect of three elements would occasion a model of four dimensions! As a matter of fact, however, we have not as yet sufficient information to make a single iron-carbon diagram with absolute certainty, nor do we know very definitely the quantitative effects produced by given quantities of the other elements I have mentioned. We must needs, therefore, confine ourselves to a consideration of the qualitative effects of the above elements on the iron-carbon solution.

THE SHAPE OF THE GRAPHITE AND THE FORM OF THE CRYSTALS.

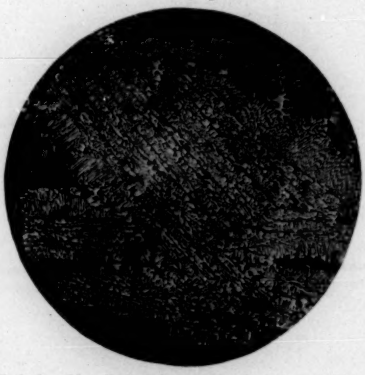
Before dealing with the effects of the other elements, I wish to call attention to two profoundly important facts, no intimation of which can be found in the iron-carbon diagram and the effects of which cannot be recorded upon it. They are, however, of vast industrial and, I think, scientific importance, and are also two factors in the final result to which I shall have occasion to refer frequently. The first is the shape of the graphite particles, and the second the form of crystallization in which the iron solidifies.

The shapes in which graphite can occur vary immensely, and

have a corresponding effect upon the structure as a whole. Graphite is, to all intents and purposes, a foreign substance in iron. In other words, we could make a steel of the same composition as a good cast iron, counting only the combined carbon, and could by suitable heat treatment bring the combined carbon into the same condition as in cast iron, and have a homogeneous material of the same nature but free from these particles of a virtually foreign substance; this would constitute an impure steel.

The smoothness and lubricating qualities of graphite are well known, as is also the fact that it is entirely without physical strength. To intersperse flakes of this material thickly through

FIG. 3.



Etched. (Magnified 38 diameters.) Spot of spotted iron.

cast iron can have obviously no other effect than to break its continuity and destroy the bonds with one another of the particles of iron proper. Good gray iron contains about 3.0 per cent. of graphite, and the specific gravity of this is about a fourth that of iron. This corresponds to about 12 per cent. by volume.

One of the things which we have discovered is that graphite in some iron is of extreme thinness and of vast extent, while in other iron it exists in scarcely more than little round knots or balls. Consider this enormous percentage by volume and the extreme thinness of the plates of graphite, which, judging from the photomicrographs, are probably less than 1/1000 of an inch thick, and

you will see what an enormous area they must have to make up 12 per cent. of the volume, and what a vast amount of damage they must do to the structure of the iron.

If we were to make up concrete and add to it 12 per cent. by volume of, say, tin scrap in small, irregular pieces, about 1 inch across, and well greased to prevent the concrete from adhering to them, and were to stir these thoroughly through the mass, and then pour the mixture into a form, do you think that the resulting concrete would be particularly valuable? If, now, instead of tin scrap an inch across, we used iron balls of about the same specific gravity

FIG. 4.

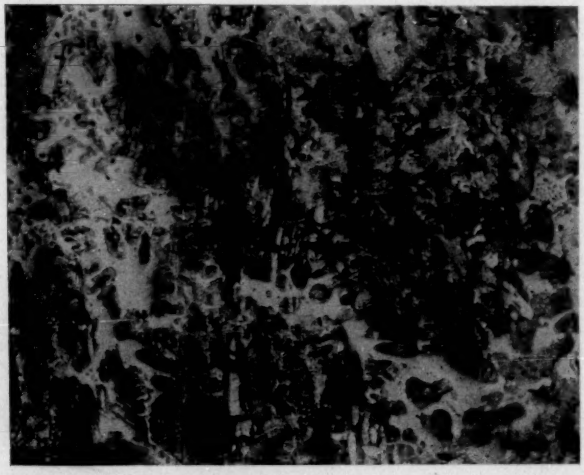
Etched. (Magnified 100 diameters.) Spot of spotted iron.

and to the same extent by weight, and stirred those thoroughly through the mass, can you doubt which concrete would be the better?

As to the form of crystallization, the eutectic of 4.20 carbon crystallizes from a pure iron-carbon solution in a series of flat plates, the cross-section of which is similar to that of a number of fern leaves laid side by side, as shown by the photomicrographs, Figs. 3 and 4. In certain kinds of iron these plates grow so large as to be plainly visible to the naked eye. When they remain white, they are as smooth as if polished, and shine brilliantly when their surfaces are exposed. If you imagine a series of blocks of mica thrown loosely into a mould, and a cement or glue poured in

to fill up the spaces between, and the resulting structure subjected to stress, you would not expect to find it very resisting, no matter how good the cement, because the blocks would cleave apart on the smooth faces of the mica. It is the same with iron which has this crystallization. No matter how good its chemical composition may be, even if the combined carbon be of the exact amount to give the greatest strength, the iron will be weak and worthless.

FIG. 5.



Etched. (Magnified 100 diameters.) Good charcoal iron, showing meshwork structure.

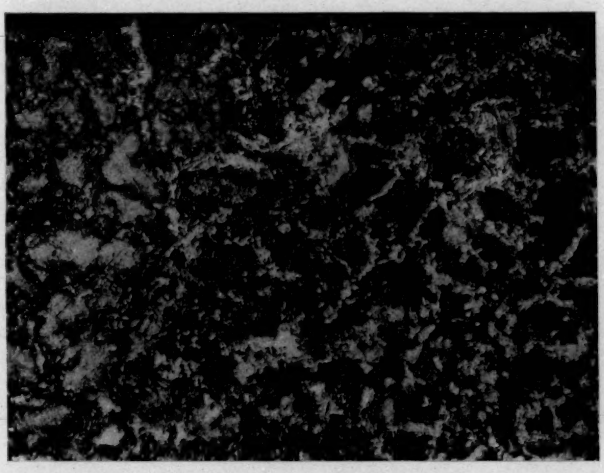
If, on the other hand, even the concentration which comes from progressive freezing results in the formation of little or no eutectic, the solution freezes into a network structure, which I have supposed is the same as that in the steel named by Professor Howe "Primaustenoid." The best illustration of this structure I have is that shown by Figs. 5 and 6. I think you will see that the structure as a whole is vastly more homogeneous than the eutectic and quite lacking in the lines of cleavage which give the latter its bad qualities, but that such lines of crystallization as do appear are in

the form of a meshwork, so that the whole structure, where not absolutely homogeneous, is interlaced together.

These are the two facts which render the amount of graphite, and even the percentage of combined carbon, matters of secondary importance, and which minimize the value of Professor Howe's brilliant generalization on that subject.

The qualities by which different irons are distinguished from one another are very many. I have classified them as follows:

FIG. 6.



Etched. (Magnified 100 diameters.) Coke iron with oxygen added. First heat of Johnson iron ever made. (Photograph due to kindness of Prof. William Campbell.)

strength, flexibility, elasticity, density or closeness of grain, fluidity, freedom from shrinkage, and machinability. These represent qualities generally desirable, but the importance of some is the greatest in one class of work and of others in other classes of work; in fact, advantages for one class of work may be positive disadvantages for another. These are matters which depend upon the purposes for which the castings are to be used, and need not be discussed in detail here.

Let us return now to the elements of prime importance—carbon, silicon, sulphur, phosphorus, oxygen, and manganese—and consider the effects which varying quantities of each of these may have upon each of above qualities of prime importance. You will see that we have here a practically unlimited number of combinations, and that it is virtually impossible to do anything more than to discuss the general results of the variations of the elements within the range of practice in different lines of foundry work.

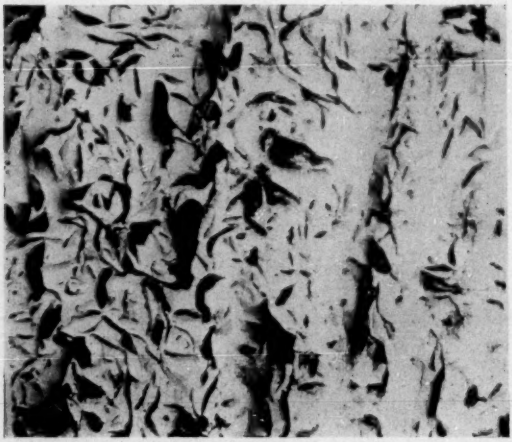
CARBON.

The subject of the effect of variations of carbon on cast iron has been neglected far too much. The carbon determination in cast iron is a difficult one, and unless made by a man with considerable experience along this line is of no value. Errors to the extent of 1 per cent. of the weight of the iron (not the carbon) have frequently been made by good and conscientious chemists through the difficulty of manipulation and, until recently, through the absence of suitable apparatus for the purpose. At the Ashland plant of the Lake Superior Iron and Chemical Company, where the researches whose results I am about to give you were begun, we introduced a long silica tube heated by an electric resistance coil, with a pyrometer to control the temperature, and burned the carbon in a stream of purified oxygen, catching the carbon dioxide in barium hydrate solution and determining its amount by titration—practically the same method as used for carbon in steel. We became so convinced of the importance of carbon determinations that we put an extra man into the laboratory in order to obtain one on every cast. Even with this excellent apparatus it took months to learn necessary temperature control and other precautions which must be taken to secure correct results. The difficulties are greatly increased by the fact that one iron will be heated to incipient fusion and sintered by a given temperature, thus sealing up some of the carbon and giving a low result, while another iron at the same temperature may not be hot enough to give off all its carbon and may show a low result on that account. I believe these difficulties of making carbon determinations at all, and of securing dependable results when they are made, have militated more against the progress of cast-iron metallurgy than any other factor.

The results of variations in carbon and their effect on the form

of crystallization were set forth at some length in a paper by myself, read before the American Institute of Mining Engineers and published in 1912, entitled "Effect of High Carbon on the Quality of Charcoal Iron." The results we obtained have been briefly mentioned above, and were that iron of the eutectic ratio crystallizes in smooth, flat plates without cohesion between either the plates in one group or between those of one group with those of another. If the iron is above the eutectic ratio,—that is, of a composition

FIG. 7.

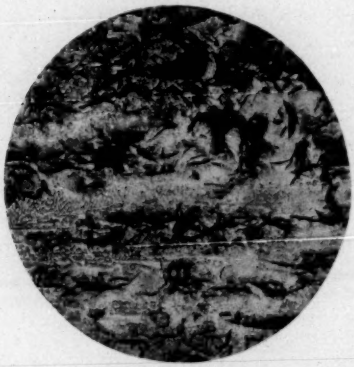


Unetched. (Magnified 70 diameters.) High cleavage iron, showing rows of graphite flakes oriented after eutectic plates from which they were focused.

represented by the right-hand branch of the iron-carbon diagram, —the excess carbon above the eutectic ratio falls out in the form of graphite as the iron cools down one of the lines *DE*, *FE*, or GE_1, and in that event, of course, the whole mass, except the ejected graphite, is at the eutectic ratio at the point of solidification and freezes as a mass of eutectic, perhaps interspersed with the particles of hypereutectic graphite. During cooling after solidification, if the silicon be high enough it forces the decomposition of the eutectic plates into ferrite, pearlite, and

graphite. These are formed in the solid condition and necessarily have the orientation of the plates of eutectic from which they are born, and, in consequence, high carbon irons, when they have sufficient silicon to make them gray, have an appearance of high cleavage, especially around the corners of the pigs and at other points where they are quickly cooled. These cleavage planes are black or gray, but are of the same general character as the brilliant white plates which occur in the same iron when it is white or mottled. They are the result of the breaking down or graphitization of the original eutectic plates (Figs. 7 and 8).

FIG. 8.



Etched. (Magnified 70 diameters.) Same as Fig. 7.

These irons have been noted for a curious peculiarity; ordinarily we expect to see the part of the iron cooled first white and the part cooled last gray, if there be any white or any gray at all, which means that the white is outside and the gray is in the centre. But in these irons the outside of the pig is gray, while there is a white chilled spot in the centre, or just above the centre, of the pig (Fig. 9). This curious phenomenon has caused much racking of wits, especially during the course of our investigation at Ashland. Finally, it occurred to me that this spot occupied the position which a segregate would take. An analysis of the spot and other portions of the pig showed that there was indeed a segregation. In irons of

moderate carbon, the portions first frozen are well below the eutectic ratio, but the portions last to freeze have the carbon concentrated in them by the selective action of freezing and therefore crystallize in the eutectic form. It is well known that the evolution of graphite is accompanied by a considerable increase in volume, and, if this be resisted with sufficient pressure, graphitization can-

FIG. 9.

Typical fracture of "spotted iron."

not take place, and the iron must remain white. I have seen a white spot produced in the centre of a pig of good iron by cooling the exterior very rapidly. This took away the heat from the outside, while the centre still remained hot enough to retain its carbon in the combined condition. The resulting contraction of the outer metal prevented the graphitization of the centre, which would have

taken place as the temperature fell, by preventing the necessary increase in volume.

It had previously been suggested by Mr. H. E. Field that this spot was caused by the pressure resulting from the contraction of the outer shell of first frozen metal upon it, but, as all pig iron solidifies under these conditions and only a small portion of it contains this spot, this solution was obviously inadequate.

The reason for the automatic formation of the white spot in these spotted irons is probably to be found in two factors:

First.—The segregate at the centre is the eutectic, and therefore has a freezing-point very decidedly lower than the outside, so that the shell is thoroughly solidified and able to exert a considerable pressure when the centre is still molten.

Second.—These spotted irons occur only within a limited range of silicon, from 0.8 per cent. down to 0.3 or 0.4. The former limit of silicon is sufficient to force graphitization, even against the resistance of the external shell. Below the latter limit the iron is practically all white, although in the case of a high carbon iron it may be heavily specked with primary graphite scattered between the blocks of eutectic plates which constitute the body of the structure.

In regard to spotted iron, it is a matter of observation that an iron may show a "spot" if quickly cooled, but will not do so if cooled slowly. For instance, the 1¼-inch test bars made at every cast at Ashland would sometimes show a spot when the pigs did not. This is evidently because of the fact brought out in the explanation of the iron-carbon diagram that the quicker the cooling and the less time allowed for the diffusion of the carbon into solidified portion of the metal, the greater the carbon concentration in the last frozen portion. Iron which, when slowly cooled, is far enough below the eutectic ratio not to undergo sufficient carbon concentration to show a "spot," undergoes, when quickly cooled, a greater carbon concentration, because there is not enough time allowed for the diffusion of the carbon throughout the mass, and so shows a spot.

These high carbon irons were noted among practical men for very deficient chilling power, a fact amply confirmed by observation of the "chill pig" at Ashland, of which one was cast in every bed, these irons having only a fraction of the chill which they should have for a given silicon. This action, may, I believe,

best be explained by reference to the well-known law of physics, that a solution of, say, common salt may be cooled below the point at which it can theoretically retain the amount of salt which was dissolved at a higher temperature, and may, if kept quiet, retain the excess to a temperature considerably lower than that of equilibrium; but if a single crystal of salt be dropped into the solution, the excess will instantly crystallize out around it, and the solution will at once drop to the equilibrium ratio. So in iron, if it be cooled more rapidly than will permit it to reach equilibrium, under ordinary conditions more carbon will be retained in combination than the equilibrium ratio would call for, but when the mass is filled with graphite flakes deposited from the molten condition (which, as I have explained, takes place with these irons) these graphite flakes act as centres of precipitation and cause *more* carbon to fall out of the solution than would do so if there were *less* total carbon present. Thus, by the aid of the microscope and with a little help from the iron-carbon diagram, we find the explanation for the characteristics of these irons easily translatable into terms of analysis, namely, their high carbon content, and so solve this long-standing riddle.

In this connection, it must be pointed out that, while 4.2 per cent. is the eutectic ratio for a pure iron-carbon alloy, the eutectic point is lowered by the addition of silicon, and probably reaches to 3.8 per cent. or even lower when the silicon reaches about 2 per cent. or more. On the other hand, other things being equal, the total carbon falls as the silicon rises beyond, say, 0.5 per cent., because carbon and silicon exert to some extent a mutually exclusive action upon each other, exactly as water saturated with calcium chloride will not take up as much common salt at a given temperature as will pure water. So, as the silicon in iron rises, the carbon falls until we reach "silvery iron"—which is a much lighter gray than ordinary iron because of the small quantity of carbon present, in spite of its being entirely graphite, the carbon with 4 per cent. silicon probably falling to below 3 per cent., as against nearly 4 per cent. in coke iron, and sometimes almost 5 per cent. in spotted charcoal iron of about 0.5 per cent. silicon.

On the other hand, the carbon falls from this point (about 0.5 per cent. silicon) as the silicon falls, because these irons are made in a colder hearth. The temperature of the iron as produced is not sufficient to enable it to take up its maximum carbon. The

fact that at this silicon percentage occurs the maximum carbon is probably also a factor in the occurrence of spotted irons within a limited range on either side of this point.

While it has been demonstrated that high carbon leads to certain exceedingly objectionable qualities in iron, it is, nevertheless, not to be assumed that high carbon is always bad, or that the lower the carbon the better the iron, since this is far from true. The hardness of chilled iron depends largely upon its content of iron carbide. This compound contains 6.66 per cent. of carbon, so that an iron with even 4 per cent. of carbon is less than two-thirds carbide or cementite. The farther we fall below 4 per cent., the smaller the percentage of carbide which can be formed from the carbon present, and, other things being equal, the softer the chill in the same proportion. In order to obtain the benefit of the high carbon, we must be able to retain the carbon in the combined condition and not have it thrown out as graphite either before or after freezing; this, you will see later, we now have a means of doing. For chilling purposes, therefore, the carbon in iron needs to be high. When the carbon falls much below 3 per cent. the character of the metal seems to change. It is probably for this reason that steel scrap, with a mixture of which by good practice castings can admittedly be made strong, can only be used in a limited proportion in chilled castings, because, if used to a greater extent, it dilutes the carbon of the whole charge so much as to impair the hardness of the chilled material.

So far as the blast furnace is concerned, we do not need to concern ourselves with carbon lower than about 3.5 in any ordinary range of silicon, since, so far as my knowledge goes, furnaces seldom make lower carbons than this under normal working conditions, although a furnace too cold to function properly has often been known to produce what is virtually wrought iron, which, of course, has too high a melting-point to run from the furnace and which causes endless trouble in consequence.

The lowest carbon I have ever seen was 3.03 per cent. This was a charcoal iron produced when the furnace was in trouble. Such an iron contains much oxygen-bearing material, which reacts with the carbon and causes the metal to be filled with a great mass of blowholes, so that each pig swells up to the section and general appearance of a well-made loaf of bread, and makes the material worthless for commercial purposes. This is known as "Spongy. No. 6."

The melting-point of the iron-carbon alloys, as may be seen from the diagrams, Figs. 1 and 2, falls from 1500° C. for pure iron to 1180° C. at the eutectic point. The lowering of the melting-point taking place along a straight line and being, therefore, proportional to the increase in carbon, consequently if the carbon be lowered to too great an extent, the melting-point becomes so much raised as to make the metal difficult to handle in the cupola, and this rise in temperature exerts a certain very detrimental influence on high-class iron, which will be shown later.

For strength alone there seems to be no doubt that a reduction in the carbon is good, even below 3 per cent., but it is probable that only material ranging from 3 per cent. to 5 per cent. in carbon should be considered cast iron. The vast majority of all the iron produced lies within the comparatively narrow limits of 3.5 to 4.25 per cent.

The other elements exert an influence on the amount of carbon which iron can contain, and also on the eutectic ratio, but these influences will be better discussed, in so far as they are known, in connection with the elements concerned.

SILICON.

Next to carbon, this is the most important component of cast iron. It varies in ordinary iron from 0.2 up to 4.0 per cent. Above 4.0 per cent. the iron passes into the field of " silvery " iron and from thence to ferro-silicon. It is extremely difficult to make iron containing less than 0.2 per cent. silicon in the coke furnace without having the sulphur run up to prohibitive limits. In the charcoal furnace iron can be produced with silicon as low as 0.10, or 0.15 in good white iron. The lowest I have ever seen it was 0.03, but this was in the spongy white iron of which I have spoken above.

Various investigations have been made as to the effect of the addition of silicon to steel. Sir Robert Hadfield conducted an extensive research on alloys of iron and silicon several years ago; this can be found in the *Journal of the Iron and Steel Institute,* 1889, vol. ii, p. 222. The effect of silicon on steel (and therefore upon the matrix of gray iron also, in a general way), within the ordinary limits in which it occurs in foundry iron, was not particularly marked, but when the silicon rose above 3.5 per cent. it diminished the ductility of the steel materially. I have already

pointed out that the strength of the matrix of gray iron proper is far less important than the extent to which it is cut up by graphite, and for this reason within ordinary limits we do not need to consider very seriously the relatively slight effect of silicon upon the metal itself (that is the matrix), but its effect upon the carbon. This, as is well known, is to force the carbon out of the combined condition into the graphitic, and this action takes place not only above the melting-point, but also down to relatively low temperatures. It is best illustrated by the fact that ordinary coke iron of more than 1.0 per cent. silicon will not show a white chill when cast against a chill block. Under any ordinary circumstances, this silicon is sufficient to force the graphitization of the carbon, in spite of the sudden cooling. Below this percentage the chilling power of the iron is roughly inversely proportional to the amount of silicon present. The iron begins to show a chill as cast from the furnace a little below 1 per cent. At 0.75 silicon it will show ordinarily one-quarter inch of white chill; at 0.5 silicon, ½ inch chill; and at 0.25 silicon it will chill clear through a depth of 2 or 3 inches, and will show much white in the pig even when slowly cooled. The completeness with which carbon is thrown out of the combined condition in unchilled iron is, in a rough way, similarly proportional to the silicon present. With 2 per cent. silicon an ordinary coke pig iron will hardly show more than 0.25 per cent. combined carbon, but the amount left in the combined condition will rise as the silicon falls, until it may be as high as 1.0 per cent. throughout the mass without the casting being chilled white on the surface, when the silicon goes down well below 1 per cent. These figures are subject to modification by considering half a dozen other factors besides silicon, and are correct only in a general way for average conditions. Definite figures are only given with great reluctance to avoid glittering generalities which sound well and mean so little.

Apart from this influence on the carbon, silicon, when it rises above 2 per cent., has the effect of hardening the matrix of the iron itself, so that an iron may be really harder to machine in consequence of having silicon added to it than it would have been with a somewhat smaller amount. There seems to be a certain probability, also, that the portion of the silicon burned out when the iron is melted in the cupola (about 0.25 per cent. in ordinary practice) remains to some extent enmeshed in the iron, and gives

rise to that bane of the foundryman's existence—" dirty spots " —in the casting. These, being in the form of silica or silicate of iron, are, of course, very hard, and vastly increase the difficulties of machining the casting which contains them, even though they may not be present in sufficient amount to cause the rejection of the piece. The effect of silicon on the strength of the iron is, of course, very different in different portions of the silicon range. The amount which converts the iron from white to dense gray increases its strength by turning brittle and crystalline cementite into tough and homogeneous pearlite, even though the latter be somewhat cut up by graphite. But as the silicon content rises further and forces the combined carbon far below the pearlite ratio (say from 0.9 down to 0.2) it weakens the matrix and simultaneously increases the deposition of graphite and the size of its particles, interrupting the continuity of the structure, and in both these ways reducing the strength of the iron.

SULPHUR.

This is the most troublesome element in the metallurgy of iron. It is present in the coke with which irons are smelted, in amount from about 0.8 per cent. up to 2 per cent. Probably in present practice it averages 1.10 per cent. Most of this is forced into the slag, but sulphur has an affinity for iron, and it is commercially impossible in coke practice to maintain the sulphur continuously much below 0.025 per cent. in ordinary iron, and only down to that amount at excessive cost in coke and limestone over that required to hold it down to 0.04. Charcoal is almost free from sulphur, and, therefore, irons with one-half this sulphur *may* be made with that fuel more easily than iron with 0.025 per cent. can be made with coke. At the same time, charcoal iron does not average below 0.018 and is seldom below 0.010. This matter has been subject to very wide misapprehension, which has been a hurt and not a help to charcoal iron. The low sulphur of charcoal iron has often been claimed as its principal virtue. With sulphur contents claimed to be " a trace " or " under 0.01 per cent." the latter statement is totally erroneous, since the sulphur in practically all charcoal iron is twice the amount claimed, and is little or no lower than that of a great deal of coke iron, while the increase in sulphur in remelting in the cupola is so much greater than that in good iron of either kind that a far greater improvement as regards this ele-

ment can, in general, be produced in the final product by a little more care in buying and analyzing the coke for the cupola, rather than the pig iron. The real virtue of charcoal iron is to be found in a totally different direction, as I shall presently endeavor to point out. Its freedom from sulphur gives charcoal the advantage which it enjoys in producing iron of higher quality than can be produced with coke, except by treatment after it leaves the furnace, but the low sulphur of the iron itself is not the reason for this superiority.

Sulphur forms with iron a sulphide which has an extremely low melting-point, and this sulphide dissolves in the iron itself in varying proportions in such a way that the sulphur exerts a threefold influence: *First,* it tends to hold the carbon in the combined condition. *Second,* it tends to liquate out into segregated spots, and, on account of its low melting temperature, sulphide of iron is extremely likely to bleed or run from the point which remains molten longest, and thereby cause a shrinkage cavity. *Third,* it has an objectionable tendency to produce high shrinkage in the iron with all the attendant difficulties of casting practice which accompany this condition.

Sulphur also has a very serious tendency to cause cracks in the iron, which is probably a result of the shrinkage. A white coke iron will often be high in sulphur, from 0.07 per cent. up to 0.2 or 0.3 per cent. in extreme cases. Such an iron, when quickly cooled with water, will crack up into little cubes like dice, each of whose faces is discolored almost black with a film of so-called "oxide color." White charcoal iron, on the other hand, of even lower silicon is tough and reasonably strong and practically never shows this tendency to break up into small pieces with oxidized faces. This statement is important and will bear some emphasis. In making coke iron low in silicon "basic" we always expected to see these conditions if the furnace became somewhat cold. On the other hand, in charcoal practice extending over three years I never recollect to have seen a single case of this, although the charcoal furnace, with the quickness of its kind, was capable of getting into just as serious difficulties as the coke furnace ever did, and did so much more frequently. Conditions are so similar in other respects that it seems to me we must assume that this objectionable tendency to form cracks is due to the presence of sulphur. In the manufacture of chilled cast-iron car wheels the sulphur must be

kept within certain limits at all hazards, as otherwise the wheels will crack under the thermal test.

For this poison in the iron we have as antidotes silicon and manganese. The silicon has no tendency to remove the sulphur, but, tending as it does to force the graphitization of the carbon, it resists the tendency of the sulphur to keep it in the combined condition. There is a rough-and ready rule for the quantitative value of this effect, which is that 10 units of silicon are required to offset the effect of one of sulphur, so that, if the sulphur in the casting be raised 0.1 per cent., the silicon would require to be raised 1.0 per cent. to offset the sulphur. It is almost certain, however, that, while the silicon prevents the action of the sulphur on carbon, it does not prevent its tendency to produce cracks and to increase shrinkage, with all its attendant evils.

The ordinary sulphur specification for pig iron is 0.05 per cent. for steel-making irons, and 0.04 or 0.035 per cent. for foundry irons. For some special grades, for which a special price is paid, even lower limits are specified. When this iron is remelted in the cupola it always takes up some sulphur from the coke in the fuel bed; this amount varies from 0.02, in extra good practice, to 0.10 or even more, in bad practice, and, while I am not one of those who sneer at the foundrymen, it does seem that they are at times inconsistent, since many of them will make a violent protest if the sulphur in the pig is 0.01 per cent. higher than the specifications call for, and will then buy a cheap coke which will raise it 0.05 per cent. higher than would a really first-class coke. I regard sulphur as the most objectionable element in cast iron with which we have to contend, and I believe the foundrymen are absolutely right in leaving no stone unturned to get the sulphur as low as possible in their castings, but sometimes it seems that they put the emphasis in the wrong place. In this connection, it may be said that the benefits in holding down the sulphur, which may be obtained by the use of lime and a little fluor spar to flux the ash and sulphur of the coke, are not as widely appreciated as they should be.

PHOSPHORUS.

The determination of the effect of phosphorus upon steel might almost be said to have been the first fragment of our modern knowledge of metallurgy. You are perhaps familiar with the story

that after Sir Henry Bessemer's first successful production of steel on an experimental scale he licensed manufacturers to use the process, but when they came to do so the product was rotten and worthless. His process was condemned, and he himself was subjected to contumely for his claims. He set out to find by chemical analysis the reason for the failure, and discovered that it lay in the phosphorus content of the iron from which the steel was made, and that, by one of those curious tricks of fortune, he had bought for his experiments the only iron in England low enough in phosphorus to make good steel. Once this was revealed, the ores which would produce iron of low enough phosphorus were located, and by using only these suitable iron for his process was obtained. With the exhaustion of the purer ores, the limit of the phosphorus set for Bessemer steel has gradually risen, until it is now about 0.09 per cent. Dozens of processes have been introduced for making good steel out of material containing more phosphorus than this without removing the latter, and it is said this may be done with some success so long as the carbon is low. When the carbon rises, however, such material always becomes brittle, uncertain, and unreliable. This has given phosphorus a bad name.

It has been assumed that because phosphorus was bad for steel it must necessarily be so for cast iron. Here again is found ignorance of that fundamental fact that a reduction of the strength of the matrix may be unimportant if a change in those conditions which affect its continuity is simultaneously made. Moreover, cast iron is a brittle material, and is not expected to be used in tension, or only under exceptional conditions, and there is no proof that phosphorus increases the brittleness of the metal until it reaches many times the limit permissible in steel. On the contrary, the Southern irons which carry in the neighborhood of 1.0 per cent. phosphorus command a premium for foundry purposes.

The effect of phosphorus is probably due to the fact that it forms one or more definite compounds with iron, which have a low melting-point, and which dissolve in the iron and lower the melting-point of the whole mass.[1] This is different from the effect of sulphur, in which the tendency seems to be for the last freezing portions to segregate after the major portion of material has solidified. The fact that phosphorus contributes to the fluidity

[1] J. E. Stead, "Iron and Phosphorus," *Journal I. and S. Inst.*, 1900, ii.

of iron is well recognized, and for many classes of castings which require to be made very thin the phosphorus is run up to 1.0 per cent. or more. There is probably little doubt, however, that this content is high enough to affect the strength of the iron adversely. For general purposes, where strength is more and fluidity less important, phosphorus from 0.5 per cent. to 0.75 per cent. is to be preferred—the latter being only for lighter castings, the former for heavier and stronger castings.

(Since the above was written, I find that the experience of the automobile manufacturers has been that phosphorus must be kept below 0.3 per cent. in their extremely complicated and difficult cylinder castings, as more than this causes a slight liquation from the heavier parts of the castings to the lighter ones and produces porosity at the former points. Castings are more difficult to make with this low phosphorus content and have to be poured considerably hotter than would otherwise be necessary, but this is the only method by which porosity can be avoided. For the ordinary run of thin foundry work, where these very severe conditions do not have to be met, higher phosphorus facilitates the work greatly.)

The effect of phosphorus up to about 0.4 per cent. seems to be to increase the strength of iron. Remelts which I have made in crucibles proved this conclusively. Two remelts were made of the same iron, to one of which phosphorus was added, raising it from 0.13 to 0.40, the other not being changed in any way. This was done on two very different irons with the same result in both cases. The strength of the best bars was materially increased by the addition of the phosphorus, and so were the depth and character of the chill. These are both most desirable qualities for material such as car wheels, but the knowledge that somewhere below 1 per cent. phosphorus begins to make the metal brittle and treacherous debars us from going beyond very moderate limits in this direction for castings in which strength and reliability are the prime consideration.

OXYGEN.

I come now to that portion of my subject in which I fear your credulity may be strained to the breaking-point. I have referred already to the investigation made at Ashland to determine the reason for the difference in quality of charcoal iron and coke iron. The first results of this investigation were those already described on the effect of high carbon, but, while these explained why some

iron was bad, they did not explain why the irons of normal carbon were stronger than the coke irons of similar analysis, and in some cases very much stronger.

I went into the investigation with a profound conviction that, next to sulphur, oxygen was the worst enemy of cast iron, but, after several months spent in a vain endeavor to confirm this hypothesis, I suddenly conceived the idea that the *presence* of oxygen, and not its absence, was that which made charcoal iron superior to coke iron. Two years of research were required before sufficient proofs of this hypothesis to justify publication were secured, but these proofs were finally obtained and the results were published in a paper before the American Institute of Mining Engineers last winter, under the title "The Effect on the Strength of Cast Iron Exerted by Oxygen, Nitrogen, and Some Other Elements." The results of this investigation were at first violently combated by some scientific metallurgists, but are now being more and more accepted.

We found, first of all, that certain irons made when the furnace had been in trouble and working cold were exceedingly strong (sometimes, though not often, almost twice as strong as irons of practically identical analysis made at other times). We found that, after being remelted in crucibles, the strong ones retained and even increased their advantage in strength over the weak ones. We found, too, after months of trial, how to make oxygen determinations in cast iron; that the strong irons contained oxygen; that the weak irons contained little or none, and that those of normal moderate strength contained an intermediate amount. By a curious coincidence, a very extensive thermal investigation of the action of charcoal and coke blast furnaces was being simultaneously undertaken for the purpose of bettering the fuel economy if possible. This investigation revealed the fact that furnaces which produce the strong irons are those which run with a deficiency of heat in their hearths and so tend to an incomplete deoxidation of the ore,—that is, tend to leave a small amount of oxygen in the iron, while those furnaces which produce the weakest irons are those which generate the greatest excess of heat in the hearth and produce the metal at a temperature the highest of any above its melting-point, ending with the electric furnace, which develops practically all its heat in the hearth, and produces its iron at an excessively high temperature, this iron being the weakest

of any variety of cast iron made. (See Figs. 10 and 11. Note the shape of the graphite and how it cuts the structure of the iron completely to pieces.)

Photomicrographs of different irons showed the reason for the increase in strength in the strong irons, since the graphite in these irons is relatively round and nodular compared with the

FIG. 10.

Unetched. (Magnified 100 diameters.) Electric furnace iron. Note extent and intersections of graphite. Strength of this iron very low, temperature of manufacture very high. Oxygen content zero.

graphite in the weak irons, which is thin and of tremendous extent, and cuts the iron like crooked knife strokes in all directions.

In Figs. 12 to 27 are shown strong irons and also weak irons of similar analysis, both before and after remelting. These figures are reproduced from the paper just mentioned. Figs 29 to 33 show in particular an extremely nodular condition of the graphite, and indicate more plainly than can any words how much stronger these irons must necessarily be than those of similar composition containing thin, flaky graphite.

The experiments described in the same paper, and briefly referred to here, are only a selection from the multitude of experiments, all pointing to the same conclusion, carried on throughout the investigation mentioned.

It seems that the effect of the oxygen is fivefold:

First, it tends to throw the graphite into the nodular condition. The theory as to the action by which this takes place has not yet

FIG. 11.

Etched. (Magnified 100 diameters.) Same as Fig. 10. Note complete absence of pearlite and joints in ferrite. These never occur in oxygen-bearing irons.

been fully confirmed by scientific investigation, but coördinates so many facts that I am satisfied it is correct, and feel justified in pointing it out here. Observation has convinced me that the irons which contain oxygen have a higher melting-point than those which do not contain it. When approaching the freezing-point, they do not freeze suddenly, as water turns to ice, but pass through a slushy or pasty stage, very different from that of hot-made coke iron. When graphitization begins in the latter it is still liquid, and

the graphite forms from the liquid absolutely without any stress whatever upon it, and is therefore free to assume whatever shape it chooses, irrespective of how great the volume and surface of that shape may be. But these oxygenated irons solidify at a higher

FIG. 12.

Unetched.

FIG. 13.

Etched. (Magnified 100 diameters.) Good iron. Silicon, 1.90; oxygen, 0.27 per cent. Breaking strength, 1.25-inch bar, 3000 pounds, 3350 pounds.

temperature, at which little or no graphitization has yet taken place, and by the time they have cooled to the temperature of graphite evolution the iron matrix has become sufficiently solid to be the dominating element in the combination. The graphite forms, but forms only against the heavy pressure exerted by the

preformed solid of the metal. In consequence, the graphite must form so as to take up minimum volume and surface. In other words, it must take this spherical form in which it is seen in Figs. 26 to 31.

FIG. 14.

Unetched.

FIG. 15.

Etched. (Magnified 100 diameters.) Poor iron. Silicon, 1.88; oxygen, 0.009 per cent. Breaking strength, 1.25-inch bar, 2500 pounds, 2900 pounds.

A confirmation of this theory is that good charcoal irons are noted for their low shrinkage, whereas bad ones are noted for their high shrinkage. This is, I believe, because when the graphite forms in the liquid, as it does in the oxygen-free irons, the iron then solidifies around it and after solidifying shrinks continuously

until cold. But when the metal solidifies *previous* to the formation of graphite, the latter forms against the resistance of the metal, which results in an increase of volume of the latter after solidification, and this expansion is deducted from the total shrinkage

FIG. 16.

Unetched.

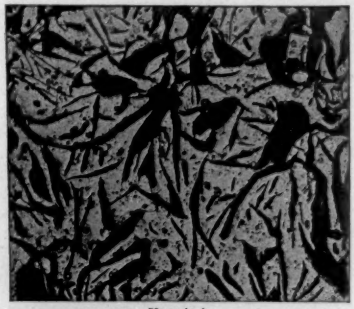
FIG. 17.

Etched. (Magnified 100 diameters.) Remelt. Silicon, 1.90 per cent. Breaking strength, 1.25-inch bar, 3150 pounds, 3200 pounds.

in the final result. This theory is not absolutely demonstrated as yet, but it is certainly in accordance with all the facts and is well worthy of an investigation, which I hope will be undertaken by some of the scientific metallurgists within a year or two so as to confirm or refute it. Whatever may be the facts in regard to

shrinkage, the increase in strength of irons which contain oxygen over those which do not contain it is a matter not open for discussion, nor is the shape into which it throws the graphite.

FIG. 18.



Unetched.

FIG. 19.

Etched. (Magnified 100 diameters.) Remelt. Silicon, 1.88 per cent. Breaking strength, 1.25-inch bar, 2600 pounds, 2700 pounds.

Second, the oxygen seems to exert another influence by changing the form of the crystallization of high carbon irons from that of the eutectic, previously shown in Fig. 3, to that of the meshwork structure, shown in Figs. 5 and 6. By this means it increases the strength of the matrix, as well as diminishes the detrimental action due to the graphite.

(To be continued)

Arc and Spark Spectra of Helium. J. STARK. (*Deutsch. Phys. Gesell. Verh.*, xvi, 10, 468.)—For a considerable time the author has investigated the difference between the arc and spark lines of elements in their canal- and cathode-ray emission, and has shown that the arc lines are emitted by the positive singly-charged atomions of the elements, while the spark lines are emitted by positive atomions doubly or multiply charged. The following results were obtained: (1) The line of wave-length 4686 Å., which has hitherto been considered a hydrogen line, is emitted strongly from the positive column of the oscillatory spark in helium free from hydrogen, so it must be assigned to helium. (2) The two known series systems of helium behave in the positive column, in cathode- and canal-rays, like arc lines. (3) The new helium line λ4686 behaves in the positive column, in canal-rays, like a spark line. (4) The peculiarities of the emission of the arc and spark spectra of helium can be explained by the fact that the former has for carrier the positive singly-charged helium atomion, the latter the positive doubly-charged atomion.

Epicassit. C. H. PROCTOR. (*The Metal Ind.*, xii, No. 11, 459.)—Epicassit is a recent German invention for coating iron or steel with pure tin, tin and lead, or a purely rust-free coating of tin, lead, and zinc. It is in the form of very finely powdered metal, mixed with an oil that acts as a flux. It is painted on the metal surface with a brush, and then the surface is heated until the applied metal melts, when it becomes thoroughly amalgamated with the surface metal, producing an extremely firm and durable coating. There are several alloys of epicassit, but the same oil flux is used for all.

A grade is pure Banca tin, free from lead.
B grade is two parts tin and one part lead.
C grade is two parts lead and one part tin.
C_1 grade is 95 per cent. lead and 5 per cent. tin.
E grade is 35 per cent. tin, 15 lead, and 50 zinc.

A Sentinel of Heat. ANON. (*Brass World*, x, No. 9, 350.)—For centuries the eye has been the judge of heat, as manifested in all its color forms, from dull red to dazzling white. Variable conditions of light and physical changes tend to render the operator's judgment inaccurate. The pyrometer and the heat cone are being used in place of the eye with profit and success. The Carl Nehls Alloy Company, 248 Brush Street, Detroit, Mich., has introduced into the field of heat measurement a small pyrometric cylinder, composed of molecular mixtures of metallic salts, known as the Sentinel pyrometer. These pyrometers can be made to melt at any desired temperature, but they solidify again if the temperature falls below that point. Two sentinels control a furnace within any desired limits of temperature, the one being liquid, while the other remains solid. Special data on heat measurements up to 2426° F. can be obtained by application for the literature of the company.

NOTES FROM THE U. S. BUREAU OF STANDARDS.*

A COMPARISON OF STELLAR RADIOMETERS AND RADIOMETRIC MEASUREMENTS ON 110 STARS.

By W. W. Coblentz.

In this paper experiments are described showing that there is but little difference in the radiation sensitivity of stellar thermocouples constructed of bismuth-platinum, and thermocouples of bismuth – bismuth + tin alloy, which have a 50 per cent. higher thermo-electric power.

Improvements are described in the method of maintaining a vacuum, by means of metallic calcium, whereby it will be possible to go to the remotest stations for making radiation measurements without carrying an expensive vacuum pump.

With this outfit measurements were made on the radiation from 112 celestial objects, including 105 stars. This includes measurements on the bright and the dark bands of Jupiter (also a pair of his satellites), the rings of Saturn, and a planetary nebula.

Quantitative measurements were made on stars down to the 5.3 magnitude, and high-grade qualitative measurements were made on stars down to the 6.7 magnitude.

It was found that red stars emit from two to three times as much total radiation as blue stars of the same photometric magnitude.

Measurements were made on the transmission of the radiations from stars and planets through an absorption cell of water. By this means it was shown that, of the total radiation emitted, the blue stars have about two times as much radiation as the yellow stars, and about three times as much radiation as the red stars, in the spectral region to which the eye is sensitive.

A stellar thermocouple and a bolometer were compared, and the former was found to be more sensitive. The conclusion arrived at is that, from the appearance of the data at hand,

* Communicated by the Bureau.

greater improvements are to be expected in stellar thermocouples than in stellar bolometers.

The object of the investigation was to obtain some estimate of the sensitivity required in order to be able to observe spectral energy curves of stars. The radiation sensitivity of the present apparatus was such that, when combined with a 3-foot reflecting telescope, a deflection of 1 mm. would have resulted when exposed to a candle placed at a distance of 53 miles. In order, however, to do much successful work on stellar spectral energy curves, a sensitivity 100 times this value is desirable. In other words, assuming that the rays are not absorbed in passing through the intervening space, the radiometric equipment (radiometer and mirror) must be sufficiently sensitive to detect the radiation from a candle removed to a distance of 500 miles. This can be accomplished by using a 7-foot mirror and by increasing the sensitivity of the present radiometer (thermocouple and galvanometer) 20 times. This increase in sensitivity is possible.

Measurements were made to determine the amount of stellar radiation falling upon 1 cm^2 of the earth's surface. It was found that the quantity is so small that it would require the radiations from *Polaris* falling upon 1 $cm.^2$ to be absorbed and conserved continuously for a period of 1,000,000 years in order to raise the temperature of 1 gramme of water 1° C. If the total radiation from all the stars falling upon 1 $cm.^2$ were thus collected and conserved it would require from 100 to 200 years to raise the temperature of 1 gramme of water 1° C. In marked contrast with this value, the solar rays can produce the same effect in about one minute.

THE TEMPERATURE COEFFICIENT OF MAGNETIC PERMEABILITY WITHIN THE WORKING RANGE.

By Raymond L. Sanford.

[ABSTRACT.]

MAGNETIC measurements at different temperatures within the atmospheric range were made on wrought iron, cast iron, and low carbon steel with different heat treatments. The results of these measurements seem to warrant the following conclusions:

1. The temperature coefficient of magnetic permeability, though

small, cannot be neglected in magnetic measurements of high accuracy.

2. On account of the wide variation in temperature coefficient, not only for different materials, but also for the same material with different heat treatments, correction cannot be made to standard temperature from data obtained from other materials.

3. Unless the temperature coefficient is known for the particular material under test, temperature control offers the only means of avoiding the error due to temperature changes, at least where errors as great as 1 per cent. are to be avoided.

CHARACTERISTIC EQUATIONS OF TUNGSTEN FILAMENT LAMPS AND THEIR APPLICATION IN HETEROCHROMATIC PHOTOMETRY.*

By G. W. Middlekauff and J. F. Skogland.

The most difficult problem in ordinary photometry is the comparison of the intensity of light sources differing widely in color. In such comparisons it is practically impossible, even for the most experienced observers, to agree in their measurements, this disagreement being due principally to difference in color vision and to difference in judgment as to when two colors viewed in the photometer are of equal intensity. Hence, especially, to establish standards, a large number of observations by different experienced observers must be taken to average out the personal errors.

One of the most convenient methods of avoiding color difference in practical photometry is by the use of colored glasses to bring the lamps to a color match; but by this method the principal difficulties are merely shifted to the problem of calibrating the glasses, a large number of which are necessary to meet the present requirements of colored light photometry.

By the method described in this paper, color differences are avoided by the use of tungsten standard lamps which are adjusted in voltage to color-match the light source to be measured, and the candlepower values of the standards at the voltage corresponding to that color are computed from the voltage at which

* Abstract of Scientific Paper No. 238.

the candlepower is known, this computation being made by the use of the voltage-candlepower equation of the standards.

In order to fully realize the advantages of this method in practice, it was necessary, first, to measure a large variety of tungsten lamps to find the relation of candlepower to voltage, and then to calculate the equation which would express this relation over a wide range of voltage or efficiency. The results were far more satisfactory than was at first anticipated.

It was found that all vacuum tungsten lamps, within a wide range of wattage, have the same voltage-current-candlepower characteristics, regardless of the make or method of manufacture. It was found, also, that not only the voltage-candlepower relation, but also the voltage-current, voltage-wattage, and voltage-watts per candle relations, could be accurately expressed by one general equation of the form $y = Ax^2 + Bx + C$. In this equation x = log voltage, y = log candlepower, log wattage, log current, or log watts per candle, and A, B, and C are constants, the values of which depend upon the significance of y. It is found most convenient to express all these variables, except watts per candle, in terms of the respective values of each at a chosen normal efficiency. In this way the constant C disappears from the equation except when y represents the watts per candle, in which case C is the log of the watts per candle chosen as normal.

The above general equation applies very exactly over the whole range investigated, namely, from 0.7 wpc. to 3.3 wpc., the latter limit extending somewhat beyond the watts per candle corresponding to color-match with 4-wpc. carbon lamps.

These equations are useful for two purposes. The international candle is maintained at the Bureau of Standards by means of 4-wpc. carbon standard lamps. If, for example, it is desired to establish a group of tungsten standards operating at 1.5 wpc., these tungsten standards would be measured directly in terms of the primary 4-wpc. carbon standards, with the voltage on the tungsten lamps so adjusted as to bring them into color-match with the primary standards. Then, knowing the voltage and corresponding efficiency of the tungsten lamps at this color, the voltage, current, watts, and candlepower corresponding to an efficiency of 1.5 wpc. are computed by means of the above characteristic equations.

Another use of these equations is in connection with tungsten

standards the values of which are known at some particular efficiency (or color). In standardizing other lamps these standards are adjusted to a color-match with the lamps to be measured, and the values of candlepower, current, etc., for each standard, at the voltage corresponding to that particular color, are determined by means of the characteristic equations.

Although these equations are simple and easy to handle, their use involves comparatively long and tedious computations. To avoid the necessity of making such computations, there has been computed and appended to the paper a set of tables from which, with the aid of an ordinary slide rule, correction factors to reduce values of candlepower, current, etc., from one efficiency to another may be read directly.

By the method described above, the photometric difficulties due to color difference are dealt with, once for all, in determining the characteristics of the tungsten lamp, and thereafter all measurements are reduced to the photometry of lights of the same color.

Copper Production in Japan. Anon. (*Metal Ind.*, xii, No. 10, 424.)—Copper is the most important mineral product of Japan. Its production has been increasing for many years in a steady ratio to the number and growing efficiency of the plants. The year 1913 was not favorable for copper mining, the prices throughout the world fluctuating so that producers were unable to foresee market conditions. Nevertheless, the production of copper in Japan increased by 3410 metric tons in 1913 over the previous record of 61,471 tons in 1912. The value of the copper production in 1912 was $20,045,526, and in 1913, $20,716,800. The greater part of the ore mined in Japan is smelted at the mines and exports in 1912 and 1913 were less than $1000.

New Flashlight Powder. Anon. (*Sci. Amer.*, cxi, No. 13, 243.)—Flashlight powders for photographic use are generally made up of magnesium, combined with a substance rich in oxygen, such as potassium chlorate, but the great drawback of such powders is that they occasion considerable smoke or fumes. Efforts made by European inventors to find a photographic powder that gives but little smoke have proved successful, and the new "Excelsior" compound uses magnesium and oxygen-bearing substances coming from the rare earths. Lanthanum peroxide was chosen, and substances were added to it analogous to those used in Welsbach lamp mantles. These form a powder giving an excellent flashlight and only one-tenth the amount of smoke, which immediately dissipates.

Cathodic Spattering of Metals. G. W. C. KAYE. (*Proc. Phys. Soc.*, xxv, part iii.)—Cathodic spattering observed when a current is sent through a discharge tube at low pressures, and resulting in the deposition of metal on the glass adjacent to the cathode, has proved very useful as a means of preparing films and mirrors, especially in the case of metals intractable by the usual methods. The spattered metal is expelled from the cathode as minute particles, apparently of the same order of magnitude as those present in colloidal solutions; they settle only on surfaces positive with respect to the cathode, and in practice the surface to be coated is connected with the anode. With certain exceptions, the amount of spattering is roughly proportional to the chemical equivalent of the metal. The effect is usually marked with palladium, platinum, gold, silver, copper, cadmium, and tin, but is small in the case of aluminum and iron in air. With cadmium and zinc a rise of temperature of the cathode greatly increases the effect. The amount of spattering is roughly proportional to the square of the current density, and is increased by increasing the potential drop at the cathode,—*e.g.*, by diminishing the pressure of the gas in the tube. Hydrogen, nitrogen, and carbon dioxide act unfavorably. Mercury vapor, oxygen, and more especially the monatomic gases, helium, neon, argon, krypton, and xenon, effect marked spattering of nearly all metals, argon being particularly effective. The appearance and properties of the deposit depend upon the nature of the gas. The spattering is usually confined mainly to points and edges of the cathode, where the potential gradient attains a maximum, and it is suggested that the blackening of X-ray tubes might be largely prevented by constructing the cathode wholly free from sharp edges and the anti-cathode of approximately spherical shape.

Novel Wax Bleaching Plant. ANON. (*Sci. Amer. Supple.*, lxxviii, No. 2015, 105.)—A novel wax bleaching plant at Brentford, England, consists essentially of an electrically driven blower, an air cooler, a battery of five ozonizers, and the vessel in which the material is treated. The ozone produced is led to the bottom of the treating vessel, and passes up through the liquid, molten wax in fine jets, which effect the bleaching.

Lead-pencil Comparison Spectrum. J. LUNT. (*Cape of Good Hope Observatory*, Ann. 10.)—For the study of many terrestrial and celestial spectra it is often necessary to arrange for a comparison spectrum capable of furnishing certain standard lines for the reduction. A convenient source for this has been found in the graphite of an ordinary lead pencil, which generally contains sufficient impurities to give lines of iron, titanium, vanadium, chromium, barium, strontium, calcium, and often gallium, scandium, yttrium, silicon, magnesium and manganese, in addition to the carbon.

THE FRANKLIN INSTITUTE

(Proceedings of the Stated Meeting held Wednesday, December 16, 1914.)

HALL OF THE FRANKLIN INSTITUTE,
PHILADELPHIA, December 16, 1914.

VICE-PRESIDENT COLEMAN SELLERS, JR., *in the Chair.*

Additions to membership since last report, 6.

Mr. George R. Henderson, Chairman of the Committee on Science and the Arts, reported the condition of the committee's work.

The following nominations were made for officers and managers to be voted for at the annual election to be held January 20, 1915:

For President (to serve one year), Walton Clark.

For Vice-President (to serve three years), James M. Dodge.

For Treasurer (to serve one year), Cyrus Borgner.

For Managers (to serve three years), J. J. Gibson, Charles Day, George A. Hoadley, Isaac Norris, Jr., Lawrence T. Paul, James S. Rogers, George R. Henderson, and Alfred W. Gibbs.

The Chairman then introduced Dr. William Barclay Parsons, of New York City, who presented an interesting communication, entitled "An American Engineer in China." Discussing China as a field for engineering developments, Dr. Parsons described the transportation facilities of the country, and also its mineral wealth and other natural resources. He gave an account of the work done up to the present time to extend and improve transportation and to develop and utilize the natural resources. In connection with further extension to this field of development, he outlined the methods of law, finance, and construction to be taken into account. He concluded with a description of some further work, in his opinion, immediately necessary. During the course of his remarks he related numerous anecdotes and personal experiences. The subject was well illustrated by lantern slides from original photographs. A rising vote of thanks was extended to the speaker.

Adjourned.

R. B. OWENS.
Secretary.

COMMITTEE ON SCIENCE AND THE ARTS.

(Abstract of Proceedings of the Stated Meeting held Wednesday, December 2, 1914.)

HALL OF THE FRANKLIN INSTITUTE,
PHILADELPHIA, December 2, 1914.

MR. J. A. P. CRISFIELD, *Chairman pro tem.*

The following reports were presented for first reading:

No. 2614.—Hardinge Conical Pebble Mill. (Further consideration.)

No. 2624.—Vanier's Potash Bulb.

R. B. OWENS,
Secretary.

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SECTIONS.

Section of Physics and Chemistry.—A stated meeting of the Section was held in the Hall of the Institute on Thursday, December 3, 1914, at 8 o'clock P.M., with Dr. Harry F. Keller in the chair. The minutes of the previous meeting were read and approved.

A. S. Eve, D.Sc., Professor of Physics in McGill University, Montreal, Canada, delivered a lecture entitled "Modern Views on the Constitution of the Atom." The evidence concerning the interior of the atom, as given by the collisions of alpha particles with molecules, by the crystal reflection of Röntgen and gamma rays, and by modern radiochemistry, was discussed, as were Planck's quantum and Bohr's speculations. The lecture was illustrated with lantern slides and charts and by means of experiments. A vote of thanks was extended to Dr. Eve, and the meeting adjourned.

JOSEPH S. HEPBURN,
Secretary,

Mechanical and Engineering Section.—A meeting of the Section was held in the Hall of the Institute on Thursday, December 10, 1914, at 8 P.M. Mr. Charles Day presided. The minutes of the previous meeting were approved as published.

The Chairman introduced Mr. R. H. M. Robinson, Managing Director of the Lake Torpedo Boat Company, Bridgeport, Conn., and formerly Naval Constructor, U. S. N., who presented a communication entitled "The Modern Submarine in Naval Warfare."

The speaker considered in some detail the power, radius of action, and armament of submarine vessels, and the degree of invulnerability of battleships against submarine attack. He outlined the tactics of submarines, considering the methods of signalling between them and other units of a fleet. He stated his belief in the necessity of two types of submarines, one for defensive use at home and the other for sea-going purposes to accompany the fleet and take part in offensive actions.

At the close of Mr. Robinson's remarks, Captain W. S. Benson, U. S. N., gave his opinion of the number of submarines required by a navy and of the manner in which they should be used.

A vote of thanks was extended Mr. Robinson, and the meeting adjourned.

WILLIAM E. BULLOCK,
Acting Secretary.

MEMBERSHIP NOTES.

ELECTIONS TO MEMBERSHIP.

(Stated Meeting, Board of Managers, December 9, 1914.)

RESIDENT.

MR. J. A. CAPSTAFF, New York Shipbuilding Company, Camden, N. J.
MR. CHARLES W. G. KING, 429 North Thirteenth Street, Philadelphia, Pa.
PROFESSOR HAROLD PENDER, University of Pennsylvania, Philadelphia, Pa.

COLONEL HARRY C. TREXLER, Allentown, Pa.
MR. CHARLES W. YOUNG, 1255 North Twenty-sixth Street, Philadelphia, Pa.

NON-RESIDENT.

MR. ERNEST L. HUFF, Natrona, Pa.

CHANGES OF ADDRESS.

MR. ROBERT BIDDLE, 3846-48 Lancaster Avenue, Philadelphia, Pa.
MR. CASPAR WISTAR HAINES, 6026 Germantown Avenue, Philadelphia, Pa.
MR. WALTER PALMER, 120 East Twenty-third Street, Chester, Pa.
MR. W. N. RUMELY, Sycamore, Ill.
MR. H. E. TROTMAN, 722 Washington Street, Camden, N. J.

NECROLOGY.

William Booth Bryan was born at Nottingham, England, in 1848. He was articled to a civil engineer of that city, and acted afterwards as assistant engineer to the Corporation of Nottingham and also to the Nottingham and Leen Valley District Sewerage Board. In 1873 he was appointed engineer to the Corporation of Burnley, and in this capacity he designed and carried out a complete sewage scheme and other important public works. Two years later he became borough and water engineer to the Corporation of Blackburn, and was responsible for the building of viaducts and bridges and for the design of a new water supply for that city. Before this latter work was completed, he was appointed, in 1882, chief engineer to the East London Water Company. He continued in this capacity until 1904, and his efforts in connection with the purification of the company's supply resulted in a considerable lowering of the typhoid death-rate in the East End of London. During his service the number of houses connected to the company's mains was practically doubled.

Mr. Bryan was elected to membership in the Institution of Civil Engineers in 1875, and was appointed a member of its Council in 1908. He was president of the Junior Institution of Engineers in 1907. He became a member of The Franklin Institute in 1902.

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BOOK NOTICES.

FOOD INDUSTRIES, AN ELEMENTARY TEXT-BOOK ON THE PRODUCTION AND MANUFACTURE OF STAPLE FOODS, by Herman T. Vulté, Ph.D., F.C.S., and Sadie B. Vanderbilt, B.S. Easton, The Chemical Publishing Company, 1914. 287 pages, illustrations, 8vo. Price, $1.75.

This is a well-printed and well-illustrated work, presenting in attractive form information concerning many of the organized industries employed in preparing raw food materials for use. After about ten pages on general questions, information is given concerning water, cereals, including methods of milling, bread-making leavening agents, starch, sugars, alcoholic beverages, the several classes of foods, and special chapters on such important foods as milk and milk products, meats, and the materials used in the cups that "cheer but not inebriate." Illustrations of apparatus and large-scale installations are freely used, so that the pupil will obtain a good idea of modern American methods in the food industries.

Evidently much close study has been given by the authors in the collection of data, and general accuracy has been secured, but on page 173 serious errors occur in reference to the effect of storage on whiskey. It is there stated that by such storage whiskey loses its fusel oil and its toxicity. The investigations of Crampton and Tolman, published some years ago, have shown that no appreciable change in the amount of fusel oil takes place even in several years' storage. The facts in regard to this matter should be set forth clearly in subsequent editions of this work.

HENRY LEFFMANN.

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Optic Projection: Principles, Installation, and use of the Magic Lantern, Projection Microscope, Reflecting Lantern, Moving-picture Machine, by Simon Henry Gage, professor of histology and embryology, emeritus, Cornell University, and Henry Phelps Gage, Ph.D. 731 pages, illustrations, 8vo. Ithaca, N. Y., Comstock Publishing Company, 1914. Price, $3.

Automatic Telephony: A Comprehensive Treatise on Automatic and Semi-automatic Systems, by Arthur Bessey Smith, E.E., and Wilson Lee Campbell, E.E. 407 pages, illustrations, plates, 8vo. New York, McGraw-Hill Book Company, 1914. Price, $4.

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The Nation's Security. How About Our Army and Navy? Speech of Hon. Augustus P. Gardner, of Massachusetts, in the House of Representatives, October 16, 1914. 8 pages, 8vo. Washington, Government Printing Office, 1914.

Judicial Recall. An address delivered at St. Louis, Mo., on September 23, 1914, before the State Bar Association of Missouri, on "The Dilemma of the Judicial Recall," by Rome G. Brown, chairman of the American Bar Association Committee to Oppose Judicial Recall. 21 pages, 8vo. Washington, Government Printing Office, 1914.

Comparative Trials of Mineral Lubricating Oils with the Addition of "Oildag." A. SAYTZEFF. (*Zeitschr. Ver. Deutsch. Ing.,* lviii, 1174.)—"Oildag" is a preparation containing pure, finely-divided graphite mixed with lubricating oil. It is manufactured and sold by the International Acheson Graphite Company, of Niagara Falls. The oils used for these trials were sold under the trade names of "Dynamo Oil E" and "Etna Engine Oil." The method of Petroff was employed for the determination of the internal friction (u), while the oil-testing machine of Martens was used to determine the resistance to friction (u), and the frictional coefficient (f). Full details of the tests, with tables and diagrams, are given. The practical results are summarized thus: (1) The value for the internal friction (u) remains fairly constant for the oils, whether treated with 1.5 per cent. oildag or not. (2) The mixture of 1.5 per cent. oildag with the mineral oils produces an almost perfect lubricating medium, and reduces the friction by 30 per cent. The mechanical friction of the thick "Etna" engine oil was diminished 7 per cent. by the addition of 1.5 per cent. oildag. (4) In all cases an addition of 1 per cent. to 2 per cent. of oildag to the oils produces a noticeable economy in oil consumption.

CURRENT TOPICS

Plastic Deformation of Steel During Overstrain. H. M. Rowe and A. G. Levy. (*Amer. Inst. Mining. Engin. Bull.*, lxxxviii, 585.)—The authors have made a microscopic study of the deformation of 0.2, 0.4, 0.75, and 1.45 per cent. carbon steels during the processes of cylindrical and conical punching, tensile testing, and wire-drawing. There are four aspects of flow in the plastic deformation of steel by overstrain: (1) The relative movements of the grains as a whole; (2) the relative movements of the cementite and pearlite within the grains; (3) the relative movements of the ferrite and cementite in the pearlite; and (4) the crystal unit slipping giving rise to the slip-bands of Ewing and Rosenhain. Intergranular movements are best shown by the uplifting of the grains on the upper surface of the plate polished previous to punching. The displacements are greater in cylindrical than in conical punching, but are confined to a narrower ring in the former case. Study of intra-pearlitic deformation shows that elongation or compression parallel to the stratification results in drawing out the cementite lines into squads and rearranging them *en echelon*. Sometimes the cementite lamellæ curve greatly, but cementite islands resulting from divorce annealing are shattered.

French Electrochemical and Electrometallurgical Industries. (*For. Off. Ann.*, Ser. No. 5324.)—A large company hitherto engaged in the manufacture of paper and sodium at Rioupéroux, in the valley of the Romanche (Isère), from whose waters it derives its power, has given up these branches of industry, as the result of a lawsuit, and has taken up instead the manufacture of ferro-alloys and calcium carbide. The French syndicate controlling the manufacture of the latter product has recently made a substantial reduction in its price, with a view of combating competition.

The company working the Paul Girod patents for the manufacture of special steels and ferro-alloys at Ugines (Savoie) and elsewhere has lately acquired further works and water-power on the Bon Naut, near St. Gervais-les-Bains. In future the manufacture of ferro-alloys will be confined to the Ugines works of the company, while that of calcium carbide will be carried on at its works in Switzerland. Licenses have been granted for working the Paul Girod processes to the Bethlehem steel works, and the French company is at present engaged in mounting extensive plant in the Ansaldo-Armstrong works in Italy and the Putiloff works in Russia. The two Paul Girod companies—for ferro-alloys and electric steels,

respectively—have lately reorganized their finances by means of a drastic reduction of capital.

Large hydro-electric works are about to be erected at Laroque-brou (Cantal) for the production of sodium nitrate in the electric furnace. The motive power will be furnished by means of a dam to be built across the Cère, causing a water-fall 488 feet high. The cost of this enterprise is estimated at £800,000. Another works for the manufacture of artificial nitrates is in contemplation at Bouvillard, near Aiguebelle (Savoie), with power derived from the Arc at La Chambre. The manufacture of electrodes is actively carried on in the works of the Electrode company situated at Venissieux, on the outskirts of Lyons, whose output exceeded 5000 tons in 1913. Up to the present time no nitrides have been produced by the Société Générale des Nitrures at its works at St. Jean de Maurienne. Arrangements are said to have been made with a Norwegian concern with works at Arendal (25,000 horse-power) for the production of nitrides on account of the French company for importation into France, this move being explained as necessitated by the lack of sufficient power in the St. Jean de Maurienne works. Another company is at present engaged in perfecting a rival process, the invention of Coutagne.

Electric Welding of Platinum Contacts. H. E. WEIGHTMAN. (*Elect. Rev. and West. Electn.*, lxiii, 686.)—Platinum contacts are now electrically welded on to springs, the principal advantage being the saving in the amount of platinum used per contact. The process is facilitated by having a thin coating of copper plate on the platinum and the current necessary for welding is thereby reduced. The welding machine is automatic, and takes a strip of platinum sheet 0.005 inch thick and 0.115 inch wide, or a coil of platinum wire, according to whether a flat or pointed contact is required. The strip or wire is fed to the clamping device, which cuts off the proper-sized piece, deposits it upon the spring, and holds it in position during welding. The welded contact is flattened or pointed by a die as it leaves the machine. Oscillograms of the current and the electromotive force during welding are given.

New White Metal Alloy. EDWARD SMITH. (*U. S. Patent 1,114,055.*)—This new alloy greatly resembles silver, and withstands atmospheric conditions to a great extent. It is suitable for the manufacture of goods which are to be silver plated. To make it, 8½ pounds of nickel are melted with a flux of silica, 20 pounds of copper are added gradually and mixed, and then 20 pounds more copper are added. Then 5 pounds of zinc are plunged beneath the molten metal, which is stirred rapidly till the whole is melted. Two and one-half pounds tin and one pound lead are added last to the liquid. Stir and heat up to 1700° F., then pour into ingot moulds.

Theory of the Coking Process. E. DONATH. (*Stahl und Eisen*, xxxiv, 60.)—A sample of coal from Rossitz, near Brunn, containing ash 4.64, water 9.66, nitrogen 1.32, hydrogen 4.86, carbon 82.88, total sulphur 3.35, sulphur in ash 0.32, combustible sulphur 3.03 per cent., when heated in an experimental coke-oven gave a molten product sufficiently fluid to flow from a small opening at the base of the oven. This product quickly solidified to a shining black mass, containing ash 10.47, water 0.50, nitrogen 0.14, hydrogen 2.99, carbon 76.86, total sulphur 3.63, sulphur in ash 2.18, combustible sulphur 1.45, oxygen 7.59 per cent. The whole of the organic constituents were volatilized when the product was heated in a covered crucible, leaving only the ash. This behavior resembles that of tallow, wax, and paraffin and some resins, and the author concludes that during the coking of a coal of this type a mixture of compounds, consisting of the degradation products of the resinous and fatty constituents of the original coal-forming materials and also the pitch-like polymerized products of distillation under pressure, is completely melted, and decomposes on further heating without leaving any carbon residue. The decomposition products react chemically with the degradation products of the cellulose and protein constituents of the coal-forming material, cementing them into a carbon-like compound or mixture of compounds. At higher temperatures the protein degradation products in the coal soften, and during the complete gasification of the coal, stable compounds are formed containing sulphur and nitrogen, and these compounds are present in the coke.

A Chemical Compound Obtained from Wool and Indigo. M. FORT and L. L. LLOYD. (*J. Soc. Dyers and Col.*, xxx. 297.)—Indigo dyed wool was extracted with boiling acetic acid and the extract diluted with water. A precipitate formed containing wool substance and indigo in fixed proportions. Similar results were obtained with other solvents and methods of isolation, and it is concluded that a definite wool-indigo lake is formed on the fibre when wool is dyed with indigo, which explains the superior fastness of indigo dyed on wool to indigo dyed on cotton.

Manufacture of Tungsten. A. JUST. (*British Patent 8956 of 1913.*)—A small percentage of another metal such as vanadium, molybdenum, chromium, or tantalum is added to the previously-prepared pure tungsten, and the mixture is gradually heated up to about 2000° C., according to the ordinary sintering process, or the mixture is melted at 3000° C. In both methods the maximum temperature must be maintained for some time to allow the tungsten to dissolve the added metal. The mixture is then suddenly cooled so that a crystalline, solid solution of one of the above metals in tungsten is obtained. This product is tempered in an electric furnace in a current of pure hydrogen or nitrogen. It is well suited for wire drawing.

Hardened Oils in Competition with Copra Oil. E. W. THOMPSON. (*Amer. Perfumer*, ix, 139.)—"Compound" lard in the United States is now made chiefly from hydrogenated cotton-seed oil. The total capacity of plant for hardening oils in Europe for 1914 is estimated at 1,375,000 barrels of 400 pounds each, and the United States output for 1913 at 500,000 barrels. The composition of margarine in Europe in 1913 is estimated at: Copra oil, 169,000; palm-kernel oil, 35,000; animal fats, 143,500; and fluid oils, 150,000 metric tons. Copra oil is being increasingly used for the purpose, and the estimated demand for 1914 is 250,000 tons, or two-thirds of the world's supply. Since 1906 the amount of copra oil produced has trebled. Small quantities of hydrogenated cotton-seed oil are now used in the manufacture of margarine in Europe.

New Powerful Search-lamp. ANON. (*Sci. Amer.*, cxi, No. 7, 111.)—A new powerful search-lamp is undergoing test at the New York Navy Yard, in which high efficiency is obtained by using a greatly concentrated arc light. Heretofore it has been found that, after a certain intensity has been reached, further increase of current results chiefly in spreading the incandescence over a larger area of the electrode. In the new search-lamp the area of the light source is even smaller than heretofore, because the electrodes are much smaller, and they are protected from rapid combustion by a cooling stream of alcohol vapor. The new electrodes are but 16 mm. in diameter, as compared with 38 millimetres for a current of 150 ampères in previous lamps. The alcohol vapor confines the illumination to the tip of the positive electrode, which hollows out into a crater filled with incandescent fumes, backed with white-hot carbon. The small spot of intense brilliancy approaches more closely to the theoretical point of light which is necessary to secure a perfectly parallel beam. The strength of the beam of the new lamp is about six times as great as that of the old. The alcohol vapor is generated by an electric resistor. To obtain a uniform bathing of the electrodes in the vapor, they are rotated.

Latent Heat of Vaporization of Carbon. C. HERING. (*Met. and Chem. Eng.*, xii, 526.)—The energy liberated when solid carbon combines with gaseous oxygen, $C + O = 26.1$ kilo-cals., and $C + O_2 = 94.3$ kilo-cals., is represented by the difference between the chemical energy of combustion and the physical energy required to render the carbon gaseous. Richards estimates the latter value at 45.7 kilo-cals. By reducing this figure from 45.7 to 42.1 (about 9 per cent.) the equations are $C + O = 26.1 + 42.1 = 68.2$ (which is identical with $CO + O = 68.2$), and $C + O_2 = 94.3 + 42.1 = 136.4$ or 68.2×2 kilo-cals. It would thus appear that carbon develops exactly as much energy in combining with the first atom of oxygen as it does with the second.

The "Half-watt" Lamp in Photography. M. LUCKIESH. (*Electr. World*, lxiv, No. 3, 129.)—The high-efficiency tungsten lamp is very valuable in photography. Much photographic work by artificial light is effected by the use of the mercury-vapor lamp, which produces powerful effects on the ordinary plate or printing paper by reason of the enormous intensity of three lines in the blue-violet region. Mr. Luckiesh's experiments show that the new gas-filled lamps will prove of considerable practical value in photography. They are much better than the ordinary tungsten lamp and as good as the direct-current open arc lamp. The half-watt lamp has considerably less actinic value than the mercury-vapor lamp, but this deficiency is largely compensated by the ease with which concentrated illumination can be obtained by the use of reflectors. A more interesting possibility resides in the use of the half-watt lamp in orthochromatic photography, although this lamp alone fails to produce a well-balanced light for orthochromatic work. However, by the use of suitable screens the light can be toned down to reproduce daylight. Perhaps the strongest point on the practical side of the matter is the ease with which the concentrated filament-types of the half-watt lamp can be made to produce a flood of light on the objects to be photographed, so that by very simple apparatus adequate light can be obtained even for instantaneous work in the studio.

Polychrome Screen Plates for Color Photography. A. and L. LUMIÈRE. (*French Patent 467,128.*)—One of the difficulties in preparing polychrome screen plates is due to the screen presenting a certain amount of color, which affects the general tone of the finished photograph. It has not been found possible to correct this by staining the gelatin emulsion, but satisfactory results have been obtained by the use of a layer of varnish of a color complementary to that of the fault in the screen. The varnish may be introduced between the screen and the emulsion or it may be applied to the glass.

Portland Cement in Peru. (*Sci. Amer.*, cxi, No. 9, 143.)—Heretofore Peru has obtained Portland cement entirely from abroad, large quantities being purchased in the United States, England, and Belgium; but recently a company has been formed in Lima to undertake the manufacture of cement. Suitable material is said to be plentiful.

Mineral Railways in Spain. (*Sci. Amer.*, cxi, No. 9, 143.)—A number of short railways, ranging from 12 to 74 miles in length, have been projected in Spain to facilitate the shipment of ores; and several of them are already under construction. These lines are located in the region between Madrid and Cordoba, and will greatly promote the development of the rich mineral district in that part of the country.

Space Lattice of Diamond. M. BORN. (*Ann. d. Physik*, xliv, No. 4, 605.)—This is a mathematical paper which may be thus summarized: (1) According to the Braggs, the diamond space lattice has the property that each carbon atom has four neighbors. Under the assumption that only these four neighbors exert molecular forces on the atom, diamond is shown to have only two molecular elasticity constants. (2) The vibrations proper to the lattice are rigorously calculated. It is shown that, as for the simplest regular lattice, the frequency is determined by a cubic. (3) The limiting case of long waves furnishes the relation between the three measurable and the two molecular elasticity constants. Among the measurable constants there is an equation of the second degree. (4) The formula for the specific heat is developed in a series in the reciprocal powers of the temperatures, according to the method of Thirring, and the first seventeen coefficients of the series are calculated. (5) The tabulation and plotting of the specific heat for various values of the elasticity constants are thus possible. (6) For an isolated carbon atom the appropriate frequency corresponds to a rest-ray wave-length of 11μ, in accordance with Einstein's statement. The frequency used by Debye may thus be calculated theoretically.

Steel Production in the United States. ANON. (*Eng. and Min. J.*, August 1, 1914.)—The Statistical Bureau of the American Iron and Steel Association states that the production of steel in the United States in 1913 was the largest ever reported. A further decrease in the make of Bessemer or converter steel, and a large increase in open-hearth steel, chiefly basic metal, are noteworthy.

The production in 1912 and 1913, in tons, was:

	1912	1913
Bessemer	10,327,901	9,545,706
Open-hearth	20,780,723	21,599,931
Crucible	121,517	121,226
Electric	18,309	30,180
Miscellaneous	2,853	3,831
Total	21,251,303	31,300,874

Included in the open-hearth steel are 1,255,305, tons made by the acid process and 2,210,718 tons produced by the duplex process, made from metal partly treated in Bessemer converters and finally purified in open-hearth furnaces. This is an increase of 772,064 tons over the previous year.

In 1913 the production of steel treated with ferrovanadium, ferrotitanium, nickel, and other alloys was 714,357 tons, a decrease of 78,144 tons from 1912. The total included 74,924 tons Bessemer steel, 213,404 acid open-hearth, 386,486 basic open-hearth, 28,279 crucible, and 11,264 tons electric and miscellaneous steel.

At the close of 1913 there were 30 plants equipped to make steel by the standard Bessemer process and 80 by the Tropenas or other modifications of that process. There were 119 basic and 93 acid open-hearth plants, 29 of them being equipped to make both acid and open-hearth steel. There were 110 crucible steel plants and 19 electric plants.

Mirror Astrolabe. H. CHRÉTIEN. (*Comptes Rendus*, clviii, 1144.)—A modification of the Claude and Driencourt prism astrolabe is proposed, substituting for the prism a mercury bath and two plane reflectors fixed at 60 degrees to each other, the angle of intersection being horizontal and normal to the plane containing the axial reflected ray. If the telescopic objective is then arranged with its axis inclining 30 degrees to the vertical, it will receive light from a star about 60 degrees altitude along two paths: the first after reflection from the mercury surface and transmission through the glass of one mirror; the second after reflection from each mirror surface. Advantages are expected on account of the homocentricity of the two luminous periods, the augmented definition, and the possibility of constructing large instruments at moderate prices.

The Velocity of Flame in Mixtures of Methane and Air. A. PARKER and A. V. RHEAD. (*Chem. Soc. Trans.*, cv, 2150.)—In connection with the study of fire-damp explosions in mines, the authors determined the velocity of flame propagation in mixtures of pure methane and air in straight horizontal tubes of glass, lead, copper, and iron, 6.5 metres long and about 2.5 cm. in diameter. The tubes were closed at one end, and the gas was ignited at the open end by a spark. The progress of the flame was recorded electrically by the fusing of thin strips of Wood's alloy, arranged 1 metre apart in the tubes. The flame travelled at a constant velocity for about 4 metres, then oscillated with increased velocity of propagation, and finally attained a constant velocity towards the end of the tube. The initial velocity varied with the strength of the mixture and with the material of the tube, being least with tubes having a high conductivity for heat. The maximum initial velocity was 70 cm. per second with a mixture containing 10 per cent. methane. The limits of inflammability occurred with methane 4.5 per cent. and 13.1 per cent. respectively.

Specially Hard Lathe Tools. ANON. (*Brass World*, x, No. 11, 441.)—Lathe tools are now made which surpass in hardness those made of the finest special steels, and which outlast them many times in cutting metals. They are composed of an alloy of cobalt, chromium, and tungsten invented by Elwood Haynes, of Kokomo, Ind., president of the Haynes Automobile Company. These alloys are also used for cutlery and take an edge equal to good steel and yet are very non-corrosive.

Three-metal Bronzes. A. M. BLOW. (*Met. and Chem. Eng.*, xii, 461.)—A description of the ternary systems: Copper-Tin with lead, zinc, phosphorus, manganese, and aluminum. *Lead* imparts plasticity to bronze, and diminishes hardness and temperature changes ("imparts a lower mutual freezing-point"). Microscopic examination shows that the lead is distributed throughout the mass. Segregation, to which bronzes rich in lead are liable, is prevented by the addition of 1 per cent. nickel, sulphur added as galena, phosphorus, or arsenic. A small addition of *zinc* does not materially alter the structure of bronzes, while ductility and tensile strength are slightly increased. Bronzes containing zinc are more easily forged and cold-rolled and are less readily corroded by sea-water. *Phosphorus* may exist entirely as solid solution (up to 1 per cent.) or as Cu_3P; it greatly increases the hardness and resistance to wear, while impairing the tensile strength, elasticity, and elongation. The maximum in commercial bronzes is about 0.8 per cent. P, with about 8 per cent. Sn. The valuable properties of *manganese* bronze are its strength and non-corrodibility; commercial products often contain more aluminum than manganese. True *aluminum* bronze seldom contains more than 11 per cent. Al; it is useful in casting, though it shrinks considerably. The addition of tin increases its ductility.

Coal-tar Dyes. ANON. (*Ch. of Comm. J.*, Oct., 1914.)—The value of the imports of coal-tar dyes to the United Kingdom from Germany in 1913 was: Alizarin and anthracene dyes, £271,119; aniline and naphthalene dyes, £1,382,478; synthetic indigo, £76,681; other kinds, £543; total, £1,730,821. Not only has the demand of the United Kingdom to be met, but also the important requirements of India, Japan, China, Turkey, Egypt, etc. India imported from Germany in 1911–12 dyes to the value of £516,939. Japan, in 1913, imported dyes to the value of £699,568. China imported from Germany in 1911 artificial indigo to the value of £575,000.

Action of Radium Emanation on Mixtures of Hydrogen and Oxygen. O. SCHEUER. (*Comptes Rendus*, clix, 423.)—In mixtures of hydrogen and oxygen produced by electrolysis, rapid combination occurs under the influence of radium emanation, whether the latter is mixed with the gases or enclosed in a bulb. The ratio of the number of molecules of gas combined to the number of pairs of ions formed per Curie-second is independent of the pressure of the gas, and varies from 5.4 : 1 to 5.6 : 1 when the emanation is mixed with the gas. The products are water and smaller quantities of hydrogen peroxide; the greater part of the former is probably produced by the decomposition of hydrogen peroxide. No ozone is produced, and only minute quantities are formed by the action of radium emanation on pure oxygen.

Rutile Deposits Yield Titanium.—Rutile, from which is derived the metal titanium, is a reddish, brownish, or nearly black mineral composed of titanium dioxide, and, though it is widely spread through the rocks, it is rarely found in large quantities. Titanium exists in larger quantity in the earth's crust than copper, lead, zinc, or any of the common metals except iron, but it is called one of the rare metals because of the lack of concentrated deposits and because the metal is so difficult to separate that it has been seen by few people.

The value of rutile arises from the use of titanium as a scavenger in molten steel and cast iron, and from the use of titanium salts in dyeing textiles and in tanning leather. The largest known deposits of rutile are at Roseland, Nelson County, Va. A few other much smaller deposits have been found in the eastern part of the United States, and still other deposits, also much smaller than those in Virginia, have been found in foreign countries. Dr. Thomas L. Watson, State geologist of Virginia, has described all the known deposits, laying stress on those in the United States, in Bulletin 580–O of the United States Geological Survey. The bulletin may be obtained free of charge by applying to the Director, United States Geological Survey, Washington, D. C.

A New Mineral Found in Tasmania. ANON. (*Sci. Amer.*, cxi, No. 11, 207.)—Many rare minerals exist in Tasmania and a new addition has been made to the list by the discovery of molybdenite, which is used in the manufacture of molybdenum steel, to which it imparts special hardness and toughness. As the present price of the mineral is about $2500 per ton, this discovery should prove of considerable value.

Uses of Tungsten.—Tungsten is used principally as an alloy of high-speed steel,—that is, steel used in making tools used in metal-turning lathes running at high speed,—to which it imparts the property of holding temper at higher temperature than carbon steels will, according to the United States Geological Survey. The now well-known ductile tungsten is used for incandescent lamps, which are fast displacing carbon lamps. Recently greatly improved lamps, in which the wire is wound in helices and in which the globes are filled with nitrogen, have produced a close approach to white light. These lamps are furnished in candlepowers up to 2000. Ductile tungsten is practically insoluble in all the common acids; its melting-point is higher than that of any other metal, its tensile strength exceeds that of iron and nickel, it is paramagnetic, it can be drawn to smaller sizes than any other metal (0.0002 inch in diameter), and its specific gravity is 70 per cent. higher than that of lead.

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